SOIL CONDITIONS

AND

PLANT GROWTH

BY

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WITH DIAGRAMS

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GENERAL PREFACE.

THE subject of Physiological Chemistry, or Biochemistry, is enlarging its borders to such an extent at the present time, that no single text-book upon the subject, without being cumbrous, can adequately deal with it as a whole, so as to give both a general and a detailed account of its present position. It is, moreover, difficult, in the case of the larger text-books, to keep abreast of so rapidly growing a science by means of new editions, and such volumes are therefore issued when much of their contents has become obsolete.

For this reason, an attempt is being made to place this branch of science in a more accessible position by issuing a series of monographs upon the various chapters of the subject, each independent of and yet dependent upon the others, so that from time to time, as new material and the demand therefor necessitate, a new edition of each monograph can be issued without re-issuing the whole series. In this way, both the expenses of publication and the expense to the purchaser will be diminished, and by a moderate outlay it will be possible to obtain a full account of any particular subject as nearly current as possible.

The editors of these monographs have kept two objects in view: firstly, that each author should be himself working at the subject with which he deals; and, secondly, that a *Bibliography*, as complete as possible, should be included, in order to avoid cross references, which are apt to be wrongly cited, and in order that each monograph may yield full and independent information of the work which has been done upon the subject.

It has been decided as a general scheme that the volumes first issued shall deal with the pure chemistry of physiological products and with certain general aspects of the subject. Subsequent monographs will be devoted to such questions as the chemistry of special tissues and particular aspects of

metabolism. So the series, if continued, will proceed from physiological chemistry to what may be now more properly termed chemical physiology. This will depend upon the success which the first series achieves, and upon the divisions of the subject which may be of interest at the time.

R. H. A. P.
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PREFACE.

I HAVE endeavoured in the following pages to give a concise account of our present knowledge of the soil as a medium for plant life. At first sight the subject appears very simple; in reality it is highly complex and trenches on several different subjects with which no one individual can claim to have any adequate knowledge, and, what is perhaps a greater disadvantage, it has grown up very unsystematically. Chemists, botanists, bacteriologists, geologists, and agriculturists have all contributed something, but usually in connection with their own special problems and not with the idea of developing a new subject. It has usually been reckoned part of the somewhat vague mixture known as agricultural chemistry, and has often been considered more suitable for farmers' lectures than for pursuit for its own sake.

As a result of its history the subject is now in a rather confused state. Suggestions thrown out by men eminent in some other branch of science have been accepted without much serious examination; illustrations used in farmers' lectures to drive home some important point to an audience before whom lucidity is above all things necessary, have acquired the force of established facts; whilst statements, and sometimes even substances, have come to be believed in for no better reason than that people have talked a great deal about them.

In recent years, however, its recognition as a basis of national wealth has given the soil a high degree of technical importance, whilst the remarkable constitution it appears to possess, the variety of its microscopic inhabitants and their close connection with plant life, all impart to its study unusual scientific interest. The time, therefore, seems ripe for a critical examination of the foundations for our beliefs, and this task is rendered easier by the advances made of late years on the Continent, in America and in this country. As the foreign literature is not generally available for English readers I have given the evidence in some detail, so that my fellow agricultural chemists may see it for themselves and the student of pure science may be able to tell us how far we are justified in using the data as we do.

E. J. R.

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CHAPTER I.

HISTORICAL AND INTRODUCTORY.

IN all ages the growth of plants has interested thoughtful men. The mystery of the change of an apparently lifeless seed to a vigorous growing plant never loses its freshness, and constitutes, indeed, no small part of the charm of gardening. The economic problems are of vital importance, and become more and more urgent as time goes on and populations increase and their needs become more complex.

There was an extensive literature on agriculture in Roman times which maintained a pre-eminent position until comparatively recently. In this we find collected many of the facts which it has subsequently been the business of agricultural chemists to classify and explain. We find also both here and in the much smaller literature of mediaeval times, certain ingenious speculations that have been justified by later work. Such for instance is Palissy's remarkable statement in 1563 (224)[1]: "You will admit that when you bring dung into the field it is to return to the soil something that has been taken away. . . . When a plant is burned it is reduced to a salty ash called alcaly by apothecaries and philosophers. . . . Every sort of plant without exception contains some kind of salt. Have you not seen certain labourers when sowing a field with wheat for the second year in succession, burn the unused wheat straw which had been taken from the field? In the ashes will be found the salt that the straw took out of the soil; if this is put back the soil is improved. Being burnt on the ground it serves as manure because it returns to the soil those substances that had been taken away." But for every speculation that has been confirmed will be found many that have not, and the beginnings of agricultural chemistry must be sought later when men had learnt the necessity for carrying on experiments.

The Search for the "Principle" of Vegetation, 1630-1750.

The earlier investigators sought for a "principle" of vegetation to account for the phenomena of soil fertility and plant growth. Van

[1] The numbers in brackets refer to the Bibliography at the end of the book.

Helmont considered he had found it in water, and thus records his famous Brussels experiment (132). "I took an earthen vessel in which I put 200 pounds of soil dried in an oven, then I moistened with rain water and pressed hard into it a shoot of willow weighing 5 pounds. After exactly five years the tree that had grown up weighed 169 pounds and about 3 ounces. But the vessel had never received anything but rain water or distilled water to moisten the soil when this was necessary, and it remained full of soil which was still tightly packed, and, lest any dust from outside should get into the soil, it was covered with a sheet of iron coated with tin but perforated with many holes. I did not take the weight of the leaves that fell in the autumn. In the end I dried the soil once more and got the same 200 pounds that I started with, less about two ounces. Therefore the 164 pounds of wood, bark, and root, arose from the water alone."

The experiment is simple and convincing, and satisfied Boyle (50) who repeated it with "squash, a kind of Indian pompion" and obtained similar results. Boyle further distilled the plants and concluded, quite justifiably from his premises, that the products obtained, "salt, spirit, earth and even oil (though that be thought of all bodies the most opposite to water) may be produced out of water". Nevertheless the conclusion is incorrect, because two factors had escaped Van Helmont's notice—the parts played by the air and by the missing two ounces of soil. But the history of this experiment is thoroughly typical of experiments in agricultural chemistry generally: in no other subject is it so easy to overlook a vital factor and draw from good experiments a conclusion that appears to be absolutely sound, but is in reality entirely wrong.

Some years later—about 1650—Glauber (107) set up the hypothesis that saltpetre is the "principle" of vegetation. Having obtained saltpetre from the earth cleared out from cattle sheds, he argued that it must have come from the urine or droppings of the animals, and must, therefore, be contained in the animal's food, *i.e.*, in plants. He also found that additions of saltpetre to the soil produced enormous increases in crop. He connected these two observations and supposed that saltpetre is the essential principle of vegetation. The fertility of the soil and the value of manures (he mentions dung, feathers, hair, horn, bones, cloth cuttings) are entirely due to saltpetre.

This view was generally accepted by later writers. Mayow (195) studied the amounts of nitre in the soil at different times of the year, and showed that it occurs in greatest quantity in spring when plants are just beginning to grow, but is not to be found "in soil on which

plants grow abundantly, the reason being that all the nitre of the soil is sucked out by the plants". Külbel (quoted in 292), on the other hand, regarded a *magma unguinosum* obtainable from humus as the "principle" sought for.

In his celebrated text-book of chemistry Boerhaave (41) taught that plants absorb the juices of the earth and then work them up into food. The raw material, the "prime radical juice of vegetables, is a compound from all the three kingdoms, *viz.*, *fossil* bodies and putrified parts of *animals* and *vegetables*". This "we look upon as the *chyle of the plant*; being chiefly found in the first order of vessels, *viz.*, in the roots and the body of the plant, which answers to the stomach and intestines of an animal".

For many years no such outstanding work as that of Glauber was published, if we except Hales' *Vegetable Staticks* (116), the interest of which is physiological rather than agricultural. Advances were, however, being made in agricultural practice. One of the most important was the introduction of the drill and the horse hoe by Jethro Tull (284), an Oxford man of a strongly practical turn of mind, who insisted on the vital importance of getting the soil into a fine crumbly state for plant growth. Tull was more than an inventor; he discussed in most picturesque language the sources of fertility in the soil. In his view it was not the juices of the earth, but the very minute particles of soil loosened by the action of moisture, that constituted the "proper pabulum" of plants. The pressure caused by the swelling of the growing roots forced these particles into the "lacteal mouths of the roots," where they entered the circulatory system. All plants lived on these particles, *i.e.*, on the same kind of food; it was incorrect to assert, as some had done, that different kinds of plants fed as differently as horses and dogs, each taking its appropriate food and no other. Plants will take in anything that comes their way, good or bad. A rotation of crops is not a necessity, but only a convenience. Conversely, any soil will nourish any plant if the temperature and water supply are properly regulated. Hoeing increased the surface of the soil or the "pasture of the plant," and also enabled the soil better to absorb the nutritious vapours condensed from the air. Dung acted in the same way, but was more costly and less efficient.

So much were Tull's writings esteemed, Cobbett tells us, that they were "plundered by English writers not a few and by Scotch in whole bandittis".

The position at the end of this period cannot better be summed up than in Tull's own words: "It is agreed that all the following materials

contribute in some manner to the increase of plants, but it is disputed which of them is that very increase or food: (1) nitre, (2) water, (3) air, (4) fire, (5) earth ".

The Search for Plant Nutrients.

1. *The Phlogistic Period*, 1750-1800.

Great interest was taken in agriculture in this country during the latter half of the eighteenth century. "The farming tribe," writes Arthur Young during this period, "is now made up of all ranks, from a duke to an apprentice." Many experiments were conducted, facts were accumulated, books written, and societies formed for promoting agriculture. The Edinburgh Society, established in 1755 for the improvement of arts and manufactures, induced Francis Home (138) "to try how far chymistry will go in settling the principles of agriculture". The whole art of agriculture, he says, centres in one point: the nourishing of plants. Investigation of fertile soils showed that they contain oil, which is therefore a food of plants. But when a soil has been exhausted by cropping, it recovers its fertility on exposure to air,[1] which therefore supplies another food. Home made pot experiments to ascertain the effect of various substances on plant growth. "The more they (*i.e.* farmers) know of the effects of different bodies on plants, the greater chance they have to discover the nourishment of plants, at least this is the only road." Saltpetre, Epsom salt, vitriolated tartar (*i.e.* potassium sulphate) all lead to increased plant growth, yet they are three distinct salts. Olive oil was also useful. It is thus clear that plant food is not one thing only, but several; he enumerates six: air, water, earth, salts of different kinds, oil, and fire in a fixed state. As further proof he shows that "all vegetables and vegetable juices afford those very principles, and no other, by all the chymical experiments which have yet been made on them with or without fire".

The book is a great advance on anything that had gone before it, not only because it recognises that plant nutrition depends on several factors, but because it indicates so clearly the two methods to be followed in studying the problem—pot cultures and plant analysis. Subsequent investigators, Wallerius (292), the Earl of Dundonald (90), and Kirwan (149) added new details but no new principles. The problem indeed was carried as far as was possible until further advances were made in plant physiology and in chemistry. The writers just

[1] Recorded by most early writers, *e.g.* Evelyn (*Terra*, 1674).

mentioned are, however, too important to be passed over completely. Wallerius, in 1761, professor of chemistry at Upsala, after analysing plants to discover the materials on which they live, and arguing that *Nutritio non fieri potest a rebus heterogeneis, sed homogeneis*, concludes that humus, being *homogeneis*, is the source of their food—the *nutritiva*—while the other soil constituents are *instrumentalia*, making the proper food mixture, dissolving and attenuating it, till it can enter the plant root. Thus chalk and probably salts help in dissolving the "fatness" of the humus. Clay helps to retain the "fatness" and prevent it being washed away by rain: sand keeps the soil open and pervious to air. The Earl of Dundonald, in 1795, adds alkaline phosphates to the list of nutritive salts, but he attaches chief importance to humus as plant food. The "oxygenation" process going on in the soil makes the organic matter insoluble and therefore useless for the plant; lime, "alkalis and other saline substances" dissolve it and change it to plant food; hence these substances should be used alternately with dung as manure. Manures were thus divided, as by Wallerius, into two classes: those that afford plant food, and those that have some indirect effect.

Throughout this period it was believed that plants could generate alkalies. "Alkalies," wrote Kirwan in 1796, "seem to be the product of the vegetable process, for either none, or scarce any, is found in the soils, or in rain water." In like manner Lampadius thought he had proved that plants could generate silica. The theory that plants agreed in all essentials with animals was still accepted by many men of science; some interesting developments were made by Erasmus Darwin in 1803 (76).

Between 1770 and 1800 work was done on the effects of vegetation on air that was destined to revolutionise the ideas of the function of plants in the economy of Nature, but its agricultural significance was not recognised until later. In 1771 Priestley (229), knowing that the atmosphere becomes vitiated by animal respiration, combustion, putrefaction, etc., and realising that some natural purification must go on, or life would not longer be possible, was led to try the effect of sprigs of living mint on vitiated air. He found that the mint made the air purer, and concludes "that plants instead of affecting the air in the same manner with animal respiration, reverse the effects of breathing, and tend to keep the atmosphere pure and wholesome, when it is become noxious in consequence of animals either living, or breathing, or dying, and putrefying in it". But he had not yet discovered oxygen, and so could not give precision to his discovery: and when, later on, he did discover oxygen and learn how to estimate it, he

unfortunately failed to confirm his earlier results because he overlooked a vital factor, the necessity of light. He was therefore unable to answer Scheele, who had insisted that plants, like animals, vitiate the air. It was Ingen-Housz (142) who reconciled both views and showed that *purification goes on in light only, whilst vitiation takes place in the darkness.* Jean Senebier at Geneva had also arrived at the same result. He also studied the converse problem—the effect of air on the plant, and in 1782 argued (262) that the increased weight of the tree in Van Helmont's experiment (p. 2) came from the fixed air. "Si donc l'air fixe, dissous dans l'eau de l'atmosphère, se combine dans la parenchyme avec la lumière et tous les autres élémens de la plante; si le phlogistique de cet air fixe est sûrement précipité dans les organes de la plante, si ce précipité reste, comme on le voit, puisque cet air fixe sort des plantes sous la forme d'air déphlogistiqué, il est clair que l'air fixe, combiné dans la plante avec la lumière, y laisse une matière qui n'y seroit pas, et mes expériences sur l'étiolement suffisent pour le démontrer." Later on Senebier translated his work into the modern terms of Lavoisier's system.

2. *The Modern Period*, 1800-1860.

We have seen that Home in 1756 pushed his inquiries as far as the methods in vogue would permit, and in consequence no marked advance was made for forty years. A new method was wanted before further progress could be made, or before the new idea introduced by Senebier could be developed. Fortunately this was soon forthcoming. To Théodore de Saussure, in 1804 (243), son of the well-known de Saussure of Geneva, is due the quantitative statistical method which more than anything else has made modern agricultural chemistry possible: which formed the basis of subsequent work by Boussingault, Liebig, Lawes and Gilbert, and indeed still remains our safest method of investigation. Senebier tells us that the elder de Saussure was well acquainted with his work, and it is therefore not surprising that the son attacked two problems that Senebier had also studied—the effect of air on plants and the nature and origin of salts in plants. De Saussure grew plants in air or in known mixtures of air and carbon dioxide, and measured the gas changes by eudiometric analysis and the changes in the plant by "carbonisation". He was thus able to demonstrate the central fact of plant respiration—the absorption of oxygen and the evolution of carbon dioxide, and further to show the decomposition of carbon dioxide and evolution of oxygen in light. Car-

bon dioxide in small quantities was a vital necessity for plants, and they perished if it was artificially removed from the air. It furnished them not only with carbon, but also with some oxygen. Water is also decomposed and fixed by plants. On comparing the amount of dry matter gained from these sources with the amount of material that can enter through the roots even under the most favourable conditions, he concludes that the soil furnished only a very small part of the plant food. Small as it is, however, this part is indispensable: it supplies nitrogen—*une partie essentielle des végétaux*—which, as he had shown, was not assimilated direct from the air; and also ash constituents, *qui peuvent contribuer à former, comme dans les animaux, leur parties solides ou osseuses.* Further he shows that the root is not a mere filter allowing any and every liquid to enter the plant; it has a special action and takes in water more readily than dissolved matter, thus effecting a concentration of the solution surrounding it; different salts, also, are absorbed to a different extent. Passing next to the composition of the plant ash, he shows that it is not constant, but varies with the nature of the soil and the age of the plant; it consists mainly, however, of alkalis and phosphates. All the constituents of the ash occur in humus. If a plant is grown from seed in water there is no gain in ash: the amount found at the end of the plant's growth is the same as was present in the seed excepting for a relatively small amount falling on the plant as dust. Thus he disposes finally of the idea that the plant *generated* potash.

After the somewhat lengthy and often wearisome works of the earlier writers it is very refreshing to turn to de Saussure's concise and logical arguments and the ample verification he gives at every stage. But for years his teachings were not accepted, nor were his methods followed.

Between 1802 and 1812 Davy gave annually some lectures on agricultural chemistry, which were published in 1813 (79), and form the earliest text-book of the modern period. Whilst no great advance was made by Davy himself (indeed his views are distinctly behind those of de Saussure) he carefully sifted the facts and hypotheses of previous writers, and gives us an account, which, however defective in places, represents the best accepted knowledge of the time, set out in the new chemical language. He does not accept de Saussure's conclusion that plants obtain their carbon chiefly from the carbonic acid of the air: some plants, he says, appear to be supplied with carbon chiefly from this source, but in general he supposes the carbon to be taken in through the roots. Oils are good manures because of the carbon and

hydrogen they contain; soot is valuable, because carbon is "in a state in which it is capable of being rendered soluble by the action of oxygen and water". Lime is useful because it dissolves hard vegetable matter. Once the organic matter has dissolved there is no advantage in letting it decompose further, putrid urine is less useful as manure than fresh urine, whilst to make the soil conditions approach those of a nitre bed, as Home had suggested, is quite wrong. All these ideas have long been given up, and indeed there never was any sound experimental evidence to support them. It is even arguable that they would not have persisted so long as they did had it not been for Davy's high reputation. His insistence on the importance of the physical properties of soils—their relationship to heat and to water—was more fortunate and marks the beginning of soil physics, afterwards developed considerably by Schübler (253). On the Continent, to an even greater extent than in England, it was held that plants drew their carbon from the soil and lived on humus, a view supported by the very high authority of Berzelius (36).

Hitherto experiments had been conducted either in the laboratory or in small pots: about 1834, however, Boussingault, who was already known as an adventurous traveller in South America, began a series of field experiments on his farm at Bechelbronn in Alsace. He reintroduced the quantitative methods of de Saussure, weighed and analysed the manures used and the crops obtained, and at the end of the rotation drew up a balance sheet, showing how far the manure had satisfied the needs of the crop and how far other sources of supply—air, rain, and soil—had been drawn upon. The results of one experiment are given in Table I. on the opposite page. "At the end of the period the soil had returned to its original state of productiveness, hence the dry matter, carbon, hydrogen, and oxygen not accounted for by the manure must have been supplied by the air and rain, and not by the soil. On the other hand, the manure afforded more mineral matter than the crop took off, the balance remaining in the soil. Other things being equal, he argued that the best rotation is one which yields the greatest amount of organic matter over and above what is present in the manure. No fewer than five rotations were studied, but it will suffice to set out only the nitrogen statistics (Table II. on the opposite page) which show a marked gain of nitrogen when the newer rotations are adopted, but not where wheat only is grown.

Now the rotation has not impoverished the soil, hence he concludes that "l'azote peut entrer directement dans l'organisme des plantes, si

TABLE I.—STATISTICS OF A ROTATION. BOUSSINGAULT (46).

	Weight in kilograms per hectare of					
	Dry Matter.	Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Mineral Matter.
1. Beets	3172	1357·7	184·0	1376·7	53·9	199·8
2. Wheat	3006	1431·6	164·4	1214·9	31·3	163·8
3. Clover hay	4029	1909·7	201·5	1523·0	84·6	310·2
4. Wheat	4208	2004·2	230·0	1700·7	43·8	229·3
Turnips (catch crop)	716	307·2	39·3	302·9	12·2	54·4
5. Oats	2347	1182·3	137·3	890·9	28·4	108·0
Total during rotation	17478	8192·7	956·5	7009·0	254·2	1065·5
Added in manure	10161	3637·6	426·8	2621·5	203·2	3271·9
Difference not accounted for, taken from air, rain, or soil.	+ 7317	+ 4555·1	+ 529·7	+ 4387·5	+ 51·0	− 2206·4

1000 kilograms per hectare = 16 cwt. per acre.

TABLE II.—NITROGEN STATISTICS OF VARIOUS ROTATIONS. BOUSSINGAULT (46).

Rotation.	Kilograms per hectare.			
	Nitrogen in Manure.	Nitrogen in Crop.	Excess in Crop over that supplied in Manure.	
			Per Rotation.	Per Annum.
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats	203·2	250·7	47·5	9·5
(1) Beets, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats	203·2	254·2	51·0	10·2
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) peas, (6) rye.	243·8	353·6	109·8	18·3
Jerusalem artichokes, two years	188·2	274·2	86·0	43·0[2]
(1) Dunged fallow, (2) wheat, (3) wheat.	82·8	87·4	4·6	1·5
Lucerne, five years	224·0	1078·0	854	170·8

leurs parties vertes sont aptes à le fixer". Boussingault's work covers the whole range of agriculture and deals with the composition of crops at different stages of their growth, with soils and with problems in animal nutrition. Some of his work was summarised by Dumas in a very striking essay (87, see also 47) that has been curiously overlooked by agricultural chemists.

During this period (1830 to 1840) Carl Sprengel was studying the ash constituents of plants, which he considered were probably essential

[1] Catch crop, *i.e.* taken in autumn after the wheat.

[2] This crop does not belong to the leguminosae, but it is possible that the nitrogen came from the soil, and that impoverishment was going on.

to nutrition (270). Schübler was working at soil physics (253), and a good deal of other work was quietly being done. No particularly important discoveries were being made, no controversies were going on, and no great amount of interest was taken in the subject.

But all this was changed in 1840 when Liebig's famous report to the British Association upon the state of organic chemistry, afterwards published as *Chemistry in its Application to Agriculture and Physiology* (172), came like a thunderbolt upon the world of science. With polished invective and a fine sarcasm he holds up to scorn the plant physiologists of his day for their continued adhesion, in spite of accumulated evidence, to the view that plants derive their carbon from the soil and not from the carbonic acid of the air. "All explanations of chemists must remain without fruit, and useless, because, even to the great leaders in physiology, carbonic acid, ammonia, acids, and bases, are sounds without meaning, words without sense, terms of an unknown language, which awake no thoughts and no associations." The experiments quoted by the physiologists in support of their view are all "valueless for the decision of any question". "These experiments are considered by them as convincing proofs, whilst they are fitted only to awake pity." Liebig's ridicule did what neither de Saussure's nor Boussingault's logic had done: it finally killed the humus theory. Only the boldest would have ventured after this to assert that plants derive their carbon from any source than carbon dioxide, although it must be admitted that we have no proof that plants really do obtain all their carbon in this way. Thirty years later, in fact, Grandeau (111) adduced evidence that humus may, after all, contribute something to the carbon supply, and his view still finds acceptance in France;[1] for this also, however, convincing proof is lacking. But for the time carbon dioxide was considered to be the sole source of the carbon of plants. Hydrogen and oxygen came from water, and nitrogen from ammonia. Certain mineral substances were essential: alkalies were needed for neutralization of the acids made by plants in the course of their vital processes, phosphates were necessary for seed formation, and potassium silicates for the development of grasses and cereals. The evidence lay in the composition of the ash: plants might absorb anything soluble from the soil, but they excreted from their roots whatever was non-essential. The fact of a substance being present was therefore sufficient proof of its necessity.

Plants, Liebig argued, have an inexhaustible supply of carbonic acid in the air. But time is saved in the early stages of plant growth if

[1] See e.g. L. Cailletet (65) and Jules Lefèvre (169).

carbonic acid is being generated in the soil, for it enters the plant root and affords extra nutriment over and above what the small leaves are taking in. Hence a supply of humus, which continuously yields carbonic acid, is advantageous. Further, the carbonic acid attacks and dissolves some of the alkali compounds of the soil and thus increases the mineral food supply. The true function of humus is to evolve carbonic acid.

The alkali compounds of the soil are not all equally soluble. A weathering process has to go on, which is facilitated by liming and cultivation, whereby the comparatively insoluble compounds are broken down to a more soluble state. The final solution is effected by acetic acid excreted by the plant root, and the dissolved material now enters the root.

The nitrogen is taken up as ammonia, which may come from the soil, from added manure, or from the air. In order that a soil may remain fertile it is necessary and sufficient to return in the form of manure the mineral constituents and the nitrogen that have been taken away. When sufficient crop analyses have been made it will be possible to draw up tables showing the farmer precisely what he must add in any particular case.

An artificial manure known as Liebig's patent manure was made upon these lines and placed on the market.

Liebig's book was meant to attract attention to the subject, and it did; it rapidly went through several editions, and as time went on Liebig developed his thesis, and gave it a quantitative form: "The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure". He further adds what afterwards became known as the Law of the Minimum, "by the deficiency or absence of *one* necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which *that one* constituent is indispensable". These and other amplifications in the third edition, 1843, gave rise to much controversy. So much did Liebig insist, and quite rightly, on the necessity for alkalis and phosphates, and so impressed was he by the gain of nitrogen in meadow land supplied with alkalis and phosphates alone, and by the continued fertility of some of the fields of Virginia and Hungary and the meadows of Holland, that he began more and more to regard the atmosphere as the source of nitrogen for plants. Some of the passages of the first and second editions urging the necessity of ammoniacal manures were deleted from the third and later editions. "If the soil be suitable, if it contains a sufficient quantity of

alkalis, phosphates, and sulphates, nothing will be wanting. The plants will derive their ammonia from the atmosphere as they do carbonic acid," he writes in the *Farmer's Magazine*. Ash analysis led him to consider the turnip as one of the plants "which contain the least amount of phosphates and therefore require the smallest quantity for their development". These and other practical deductions were seized upon and shown to be erroneous by Lawes (160-162) who had for some years been conducting vegetation experiments. Lawes does not discuss the theory as such, but tests the deductions Liebig himself draws and finds them wrong. Further trouble was in store for Liebig; his patent manure when tried in practice *had failed*. This was unfortunate, and the impression in England at any rate, was, in Philip Pusey's words: "The mineral theory, too hastily adopted by Liebig, namely, that crops rise and fall in direct proportion to the quantity of mineral substances present in the soil, or to the addition or abstraction of these substances which are added in the manure, has received its death-blow from the experiments of Mr. Lawes".

And yet the failure of the patent manure was not entirely the fault of the theory, but only affords further proof of the numerous pitfalls of the subject. The manure was sound in that it contained potassium compounds and phosphates (it ought of course to have contained nitrogen compounds), but it was unfortunately rendered insoluble by fusion with lime and calcium phosphate so that it should not too readily wash out in the drainage water. Not till Way had shown in 1850 that *soil precipitates soluble salts of ammonium, potassium and phosphates* was the futility of the fusion process discovered, and Liebig saw the error he had made (173).

Meanwhile he continued to defend his position in the controversy with Lawes and Gilbert. It is not possible in this short sketch to go into details, but by 1855 the following points were settled by the experiments made at Rothamsted to test the various points raised:—

(1) Crops require phosphates and salts of the alkalis, but the composition of the ash does not afford reliable information as to the amounts of each constituent needed, *e.g.* turnips require large amounts of phosphates, although only little is present in their ash.

(2) Non-leguminous crops require a supply of some nitrogenous compounds, nitrates and ammonium salts being almost equally good. Without an adequate supply no increases of growth are obtained, even when ash constituents are added. The amount of ammonia obtainable from the atmosphere is insufficient for the needs of crops. Leguminous crops behaved abnormally.

(3) Soil fertility may be maintained for some years at least by means of artificial manures.

(4) The beneficial effect of fallowing lies in the increase brought about in the available nitrogen compounds in the soil.

Although many of Liebig's statements were shown to be wrong, the main outline of his theory as first enunciated stands. It is no detraction that de Saussure had earlier published a somewhat similar, but less definite view of nutrition: Liebig had brought matters to a head and made men look at their cherished, but unexamined, convictions. The effect of the stimulus he gave can hardly be over-estimated, and before he had finished, the essential facts of plant nutrition were settled and the lines were laid down along which scientific manuring was to be developed. The water cultures of Knop and other plant physiologists showed conclusively that potassium, magnesium, calcium, iron, phosphorus, along with sulphur, carbon, nitrogen, hydrogen, and oxygen are all necessary for plant life. The list differs from Liebig's only in the addition of iron and the withdrawal of silica; but even silica, although not strictly essential, is advantageous to cereals.

In two directions, however, the controversies went on for many years. Farmers were slow to believe that "chemical manures" could ever do more than stimulate the crop, and declared they must ultimately exhaust the ground. The Rothamsted plots falsified this prediction; manured year after year with the same substances and sown always with the same crops, they even now after sixty years of chemical manuring continue to produce good crops, although secondary effects have sometimes set in. In France the great missionary was Georges Ville, whose lectures were given at the experimental farm at Vincennes during 1867 and 1874-5 (286). He went even further than Lawes and Gilbert, and maintained that artificial manures were not only more remunerative than dung, but were the only way of keeping up fertility. In recommending mixtures of salts for manure he was not guided by ash analysis but by field trials. For each crop one of the four constituents, nitrogen compounds, phosphates, lime, and potassium compounds (he did not consider it necessary to add any others to his manures) was found by trial to be more wanted than the others and was therefore called the "dominant" constituent. Thus nitrogen was the dominant for cereals and beetroot, potassium for potatoes and vines, phosphates for the sugar cane. An excess of the dominant constituent was always added to the crop manure. The composition of the soil had to be taken into account, but soil analysis was no good for the purpose. Instead he drew up a simple scheme of plot

trials to enable farmers to determine for themselves just what nutrient was lacking in their soil. His method was thus essentially empirical, but it still remains the best we have; his view that chemical manures are always better and cheaper than dung is, however, too narrow and has not survived.

The second controversy dealt with the source of nitrogen in plants. Priestley had stated that a plant of *Epilobium hirsutum* placed in a small vessel absorbed during the course of the month seven-eighths of the air present. De Saussure, however, denied that plants assimilated gaseous nitrogen. Boussingault's pot-experiments showed that peas and clover could get nitrogen from the air while wheat could not (45) and his rotation experiments emphasised this distinction. He himself did not make as much of this discovery as he might have done, but Dumas (87) fully realised its importance.

Liebig, as we have seen, maintained that ammonia, but not gaseous nitrogen, was taken up by plants, a view confirmed by Lawes, Gilbert, and Pugh (164) in the most rigid demonstration that had yet been attempted. Plants of several natural orders, including the leguminosæ, were grown in surroundings free from ammonia or any other nitrogen compound. The soil was burnt to remove all trace of nitrogen compounds while the plants were kept throughout the experiment under glass shades, but supplied with washed and purified air and with pure water. In spite of the ample supply of mineral food the plants languished and died: the conclusion seemed irresistible that plants could not utilise gaseous nitrogen. For all non-leguminous crops this conclusion agreed with the results of field trials. But there remained the very troublesome fact that leguminous crops required no nitrogenous manure and yet they contained large quantities of nitrogen and also enriched the soil considerably in this element. Where had the nitrogen come from? The amount of combined nitrogen brought down by the rain was found to be far too small to account for the result. For years experiments were carried on, but the problem remained unsolved. Once again an investigation in agricultural chemistry had been brought to a standstill for want of new methods of attack.

The Beginnings of Soil Bacteriology.

It had been a maxim with the older agricultural chemists that "corruption is the mother of vegetation". Liebig had taught that nitrogenous organic matter decayed in the soil by a chemical process "eremacausis" with formation of ammonia, the essential nitro-

genous food, a small part of which was further converted into nitric acid, which apparently also served as a plant nutrient (174). During the sixties and seventies great advances were being made in bacteriology and it was definitely established that bacteria bring about putrefaction, decomposition and other changes; it was therefore conceivable that they were the active agents in the soil and that the process of decomposition there taking place was not purely chemical as Liebig had asserted. Pasteur himself had expressed the opinion that nitrification—the curious change of ammonia to nitrate known to take place in soils—was a bacterial process. The new knowledge was first brought to bear on agricultural problems by Schloesing and Müntz (244) in 1877 during a study of the purification of sewage water by land filters. A continuous stream of sewage was allowed to trickle down a column of sand and limestone so slowly that it took eight days to pass. For the first twenty days the ammonia in the sewage was not affected, then it began to be converted into nitrate; finally all the ammonia was converted during its passage through the column and nitrates alone were found in the issuing liquid. Why, asked the authors, was there a delay of twenty days before nitrification began? If the process were simply chemical, oxidation should begin at once. They therefore examined the possibility of bacterial action and found that the process was entirely stopped by a little chloroform vapour, but could be started again after the chloroform was removed by adding a little turbid extract of dry soil. Nitrification was thus shown to be due to micro-organisms—"organised ferments" to use their own expression.

Warington (296) had been investigating the nitrates in the Rothamsted soils, and at once applied the new discovery to soil processes. He showed that nitrification in the soil is stopped by chloroform and carbon disulphide; further, that solutions of ammonium salts could be nitrified by adding a trace of soil. By a careful series of experiments described in his four papers to the Chemical Society he found that there were two stages in the process and two distinct organisms: the ammonia was first converted into nitrite and then to nitrate. But he failed altogether to obtain the organisms in spite of some years of study by the gelatin plate methods then in vogue. The reason was discovered later: the organisms will not grow in presence of nitrogenous organic matter. Not till 1890 did Winogradsky (311) succeed in isolating them, and thus complete the evidence.

Warington established definitely the fact that nitrogen compounds rapidly change to nitrates in the soil, so that whatever compound is

supplied as manure plants get practically nothing but nitrate as food. This closed the long discussion as to the nitrogenous food of non-leguminous plants: in natural conditions they take up nitrates only (or at any rate chiefly), because the activities of the nitrifying organisms leave them no option. The view that plants assimilate gaseous nitrogen has from time to time been revived, but has not been taken seriously.

The apparently hopeless problem of the nitrogen nutrition of leguminous plants was soon to be solved. In a striking series of sand cultures Hellriegel and Wilfarth (130) showed that the growth of non-leguminous plants, barley, oats, etc., was directly proportional to the amount of nitrate supplied, the duplicate pots agreeing satisfactorily; while in the case of leguminous plants no sort of relationship existed and duplicate pots failed to agree. After the seedling stage was passed the leguminous plants grown without nitrate made no further progress for a time, then some of them started to grow and did well, while others failed. This period of no growth was not seen where nitrate was supplied. Two of their experiments are given in Table III.

TABLE III.—RELATION BETWEEN NITROGEN SUPPLY AND PLANT GROWTH. HELLRIEGEL AND WILFARTH (130).

Nitrogen in the calcium nitrate supplied per pot, grams	none	·056	·112	·168	·224	·336
Weight of oats obtained (grain and straw)	·3605 ·4191	5·9024 5·8510 5·2867	10·9814 10·9413	15·9974	21·2732 21·4409	30·1750
Weight of peas obtained (grain and straw)	·551 3·496 5·233	·9776 1·3037 4·1283	4·9146 9·7671 8·4969	5·6185	9·7252 6·6458	11·3520

Analysis showed that the nitrogen contained in the oat crop and sand at the end of the experiment was always a little less than was originally supplied, but was distinctly greater in the case of peas; the gain in three cases amounted to ·910, 1·242 and ·789 grm. per pot respectively. They drew two conclusions: (1) the peas took their nitrogen from the air; (2) the process of nitrogen assimilation was conditioned by some factor that did not come into their experiment except by chance. In trying to frame an explanation they connected two facts that were already known. Berthelot (26) had made experiments to show that certain micro-organisms in the soil can assimilate gaseous nitrogen. It was known to botanists that the nodules on the

roots of leguminosæ contained bacteria.[1] Hellriegel and Wilfarth, therefore, supposed that the bacteria in the nodules assimilated gaseous nitrogen, and then handed on some of the resulting nitrogenous compounds to the plant. This hypothesis was shown to be well founded by the following facts :—

1. In absence of nitrates peas made only small growth and developed no nodules in sterilised sand; when calcium nitrate was added they behaved like oats and barley, giving regular increases in crop for each increment of nitrates (the discordant results of Table 2 were obtained on unsterilised sand).

2. They grew well and developed nodules in sterilised sand watered with an extract of arable soil.

3. They sometimes did well and sometimes failed when grown without soil extract and without nitrate in *unsterilised* sand, which might or might not contain the necessary organisms. An extract that worked well for peas might be without effect on lupins or serradella. In other words, the organism is specific.

Hellriegel and Wilfarth read their paper and exhibited some of their plants at the Naturforscher-Versammlung at Berlin in 1886. Gilbert was present at the meeting, and on returning to Rothamsted repeated and confirmed the experiments (165). At a later date Schloesing fils and Laurent (247) showed that the weight of nitrogen absorbed from the air was approximately equal to the gain by the plant and the soil and thus finally clinched the evidence :—

	Control.	Peas.	Mustard.	Cress.	Spurge.
Nitrogen lost from the air, mgm. . .	1·0	134·6	− 2·6	− 3·8	− 2·4
Nitrogen gained by crop and soil, mgm.	4·0	142·4	− 2·5	2·0	3·2

The organism was isolated by Beijerinck (p. 95) and called *Bacterium radicicola*.

Thus another great controversy came to an end and the discrepancy between the field trials and the laboratory experiments of Lawes, Gilbert and Pugh was cleared up. The laboratory experiments gave the correct conclusion that leguminous plants, like non-leguminous plants, have themselves no power of assimilating gaseous nitrogen; this power belongs to the bacteria associated with them. But so carefully was all organic matter removed from the soil, the apparatus and the air in endeavouring to exclude all trace of ammonia, that there was no

[1] This had been demonstrated by Woronin in 1866 (322). Eriksson in 1874 (95) made an admirable investigation, while Brunchorst in 1885 (64) gave the name "bacteroid".

chance of infection with the necessary bacteria. Hence no assimilation could go on. In the field trials the bacteria were active, and here there was a gain of nitrogen.

The general conclusion that bacteria are the real makers of plant food in the soil, and are, therefore, essential to the growth of all plants, was developed by Wollny (317) and Berthelot (28). It was supposed to be proved by Laurent's experiments (159, see also 86). He grew buckwheat on humus obtained from well-rotted dung, and found that plants grew well on the untreated humus, but only badly on the humus sterilised by heat. When, however, soil bacteria were added to the sterilised humus (by adding an aqueous extract of unsterilised soil) he got good growth again. The experiment looks convincing, but is really unsound. When a rich soil is heated some substance is formed toxic to plants. The failure of the plants on the sterilised humus was, therefore, not due to absence of bacteria, but to the presence of a toxin. No one has yet succeeded in carrying out this fundamental experiment of growing plants in two soils differing only in that one contains bacteria while the other does not.

The close connection between bacterial activity and the nutrition of plants is, however, fully justified by many experiments, and forms the basis of our modern conception of the soil as a producer of crops, as will appear in the following chapters.

CHAPTER II.

THE REQUIREMENTS OF PLANTS.

FOR a true understanding of our subject it is necessary at the outset to realise the conditions and factors influencing the growth of plants. We have to look upon the plant as a synthetic agent and accumulator of energy, taking up simple substances like carbon dioxide, water, nitrates, phosphates, potassium salts, etc., and manufacturing complex sugars, starch, cellulose, proteins, nucleo-proteins, essential oils, colouring matters and a host of other substances. The natural object of the processes is to produce seeds containing the embryo and a supply of food for the young plant to draw upon till such time as it can synthesise its own food. In agriculture, however, the stored up food material is taken at whatever stage is convenient and constitutes the food and energy supply of animals and of men.

As the processes of the plant are endothermic the energy of the sun's rays is indispensable to them. The transforming agent is chlorophyll, the ordinary green colouring matter of the leaf. Since the reactions have all to go at ordinary temperatures catalysts are necessary to accelerate changes that would otherwise be very slow; these are supplied by the protoplasm and the numerous enzymes. The whole cycle of changes collectively spoken of as plant growth represents the net gain from two opposite processes, (1) a constructive process of at least three stages: synthesis of complex material, translocation of the synthesised food to centres of growth, and building up of the food into plant tissues or reserves, (2) a respiratory process whereby carbohydrate material is broken down and carbon dioxide evolved. The synthesis is of two types: photosynthesis, in which sugar is produced; and another, not specifically named, giving rise to protein. Photosynthesis, as its name implies, takes place only in light and is restricted to the chlorophyll cells. The initial substances are carbon dioxide and water; in a very short time the apparent end products, starch and oxygen (equal in volume to the carbon dioxide), appear. It is shown, however, by the researches of Brown and others that the real end product is cane sugar, starch only being formed when

the concentration of the cell sap becomes high. Synthesis of protein, on the other hand, is not restricted to the chlorophyll cells nor is it directly dependent on light,[1] but it does not start as low down as carbohydrate synthesis, the initial substances being, apparently, sugar and nitrates.

For the translocation of food materials from one part of the plant to another they have to be changed, if necessary, into simpler soluble substances, starch being converted into sugars and protein into certain decomposition products; this change is effected by enzymes. For storage purposes it is usually necessary that the substances should be insoluble and they are therefore reconverted into complex bodies.

The destructive process, respiration, in which oxygen is absorbed, sugar oxidised and carbon dioxide evolved (in rather less volume than that of the oxygen) is a general property of protoplasm. It takes place throughout the whole life of the plant and in all the living cells; during the growing period it is of course on a smaller scale than the synthetic processes, but during both germination and ripening it is on a larger scale, consequently there is a loss of weight.

These separate processes—assimilation, translocation, metabolism, respiration—all seem to follow the ordinary laws of chemical reaction, the only modification necessary being the introduction of a time factor, since protoplasm will not indefinitely maintain its powers. For instance, in the classical experiments of Blackman and of Miss Matthaei (194), the effect of temperature on assimilation, *all other factors being eliminated*, was precisely that obtaining in an ordinary chemical reaction; so also for respiration. Miss Matthaei found that the amounts of carbon dioxide assimilated by a cherry laurel leaf per 50 sq. cms. (about 8 sq. ins.) per hour at various temperatures were:—

Temperature, degrees C.	− 6°	+ 8·8°	11·4°	15°	23·7°	30·5°	37·5°	40·5°	43° [2]
Weight of CO_2 assimilated, grams	·0002	·0038	·0048	·0070	·0102	·0157	·0238	·0149	·0102

By interpolation the values at 0°, 10°, 20° etc. can be found, and the rate of assimilation is thus seen to double, and more than double, for every increase of 10°, the usual order of increase in chemical reactions:—[3]

[1] Confirmed by Zaleski's recent experiments (323).

[2] The normal rates were only maintained for a short time at the higher temperatures.

[3] A list of the papers dealing with the temperature coefficient for cell growth is given in *Science*, 6th November, 1908.

Temperature	0°	10°	20°	30°	37°
Amount of CO_2 assimilated per hour	175	42	89	157	238
Increased rate for 10° C.	—	2·4	2·1	1·8	1·8

But, on the other hand, the effect of temperature on the *rate of growth of a plant is in no wise like its effect in accelerating chemical* change. Bialoblocki's (37) results with barley were as follows:—

Temperature	[0]	10°	20°	30°	40°
Dry matter formed, grams . .	[nil]	7·64	8·22	3·85	0·93

The two curves are shown in Fig. 1 ; the difference between them is

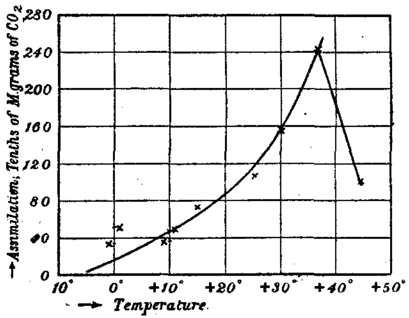

FIG. 1A.—Relation between Temperature and Assimilation. (Miss Matthaei.)

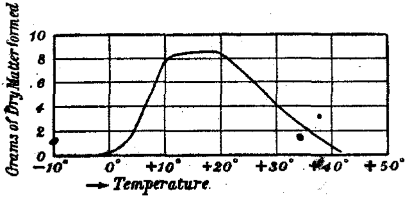

FIG. 1B.—Relation between Temperature and Plant Growth. (Bialoblocki.)

of fundamental importance to our subject and must be discussed in some detail.

Each of the separate processes—assimilation, respiration, etc. gives, so far as is known, curves like Fig. 1*a* continuous over the whole

range of temperature nearly up to the death point. At higher temperatures it is necessary to work for a short period only, so as to eliminate the element of fatigue, but there is no break in the curve.

For the growth of the plant, however, it is necessary that all the processes should work harmoniously together, and that the protoplasm should remain healthy and vigorous. Now the temperature range over which protoplasm lives and the somewhat delicate adjustment of the processes holds together, is very restricted; beyond a certain point, further temperature increases do not cause more growth, but throw the adjustment out of gear and act adversely on the protoplasm. Thus we get a bending over of the curve.

The distinction is well brought out in the work of Brown and Escombe (59) on the influence of varying partial pressures of carbon dioxide on photosynthesis. So long as photosynthesis *alone* was considered, and other factors eliminated, its amount was proportional to the partial pressure:—

	Experiment 1.		Experiment 2.	
	a.	*b.*	*a.*	*b.*
Partial pressures of CO_2, parts per 10,000	2·22	14·82	2·25	9·95
Ratio	1	6·6	1	4·4
CO_2 absorbed by leaf per sq. m. per hour, c.cs.	248·2	1802·8	309	1639
Ratio	1	7·2	1	5·3

But when *plants were grown* in atmospheres containing various amounts of carbon dioxide then a wholly different relationship was observed:—[1]

	Experiment 1.		Experiment 2.	
	a.	*b.*	*a.*	*b.*
Partial pressures of CO_2, parts per 10,000	2·9	5·4	2·9	12
Ratio	1	1·9	1	3
Dry weight of beans found after ten days, grams	·856	·843	·872	8·14
Ratio	1	1	1	0·9

Assimilation must have gone on at the accelerated rate in the beginning, but the other processes were unable to keep pace and so they set a limit to the speed of growth. A factor that thus proves

[1] The details of these experiments have been criticised by Demoussy (83 and 84), but the general conclusion is probably sound.

insufficient and stops what ought to be a continuous process is called by Blackman (40) a "limiting factor".

An instance of a limiting factor is afforded by Miss Matthaei's work on the rate of assimilation in cherry laurel leaves. Working with artificial light of low intensity she found that assimilation increased with the temperature to a certain point, but then remained constant; the light was insufficient for quicker photosynthesis. When the light was increased a higher speed of photosynthesis became possible, until with full light the ordinary logarithmic curve was obtained.

When all other factors are sufficiently supplied a limit is finally set by the inability of the protoplasm to do more than a certain amount of work.

We can now draw up our general curve showing the relationship between the supply of any particular factor and the amount of plant growth. It consists of either two or three parts (Fig. 2). In the first

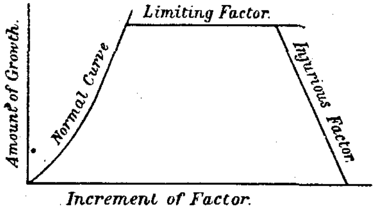

FIG. 2.—General Relation between any particular Factor and Plant Growth.

part all the processes in the plant are working harmoniously and the plant remains healthy; here an increase in the factor causes an increase in the amount of growth, and the curve is similar to that obtained for any single process considered separately. In the second part some limiting factor comes into play, such as an insufficiency of something essential, or an inability of some process to go any faster; the rate of growth cannot, therefore, show any further increase. It may happen that further increase of the factor even acts injuriously by bringing about a secondary adverse effect such as injury to the protoplasm or to the medium in which the plant is growing.

Mitscherlich has shown (201 and 202) that in some cases, where the adverse effect is absent, the curves can be expressed by a simple equation. If all the conditions were ideal a certain maximum yield would be obtained, but in so far as any essential factor is deficient, there is a corresponding shortage in the yield. The yield rises if some

of the lacking factor is added; and goes up all the further, the lower it had previously fallen. Mitscherlich puts this as follows: the increase of crop produced by unit increment of the lacking factor is proportional to the decrement from the maximum. The advantage of this form is that it can be expressed mathematically:—

$$\frac{dy}{dx} = (A - y)k \text{ or } \log_e (A - y) = c - kx,$$

where y is the yield obtained when x = the amount of the factor present and A is the maximum yield obtainable if the factor were present in excess, this being calculated from the equation.[1]

Mitscherlich's own experiments were made with oats grown in sand cultures supplied with excess of all nutrients excepting phosphate. This constituted the valuable x: the yields actually attained when monocalcium phosphate was used and those calculated from the equation are shown in Table IV. (p. 25). It will be noticed that there is a kink in the curve at the point where 0·2 grammes of phosphate is supplied. This kink seems to invariably occur, and is dealt with on p. 32.

Experiments were also made with di- and tri-calcic phosphates and constants were calculated corresponding to k. The ratio of these constants $\frac{k_2 \text{ (di-calcic phosphate)}}{k_1 \text{ (mono-calcic phosphate)}}$ is a measure of the relative nutrient efficiency of the two salts: k is therefore called the efficiency value (*wirkungswert*). There are some very attractive possibilities about

[1] The method of calculation is as follows: Obtain two equations by substituting two of the numerical values of x and y obtained experimentally. Calling these numbers x_1, x_2, etc., the equations are

$$\log_e (A - y_1) = c - kx_1 \quad . \quad . \quad . \quad (1)$$

$$\log_e (A - y_2) = c - kx_2 \quad . \quad . \quad . \quad (2)$$

Then by subtraction $\log (A - y_1) - \log (A - y_2) = k (x_2 - x_1)$ . . . (3)

Obtain another equation like (3) but select the numerical values so that

$$x_3 - x_2 = x_2 - x$$

$$\log_e (A - y_3) - \log_e (A - y_2) = k (x_3 - x_2) \quad . \quad . \quad . \quad (4)$$

By subtracting (4) from (3) $\log_e (A - y_1) + \log_e (A - y_3) = 2 \log_e (A - y_2)$,

$$\textit{i.e.,} \quad \frac{(A - y_3)(A - y_1)}{(A - y_2)^2} = 1.$$

Since y_1, y_2, and y_3 are all numbers, the value of A is easily calculated.
The value of k is then found from equation (3)

$$k = \frac{\log_e (A - y_1) - \log_e (A - y_2)}{x_2 - x_1}.$$

As all the quantities on the right-hand side are numbers the value of k is readily obtained. This method is further discussed by Th. Pfeiffer, E. Blanck and M. Flügel, *Wasser und Licht als Vegetationsfactoren und ihre Beziehungen zum Gesetze vom Minimum* (Landw. Versuchs-Stat., 1912, lxxvi., 169-236).

TABLE IV.—YIELD OF OATS WITH DIFFERENT DRESSINGS OF PHOSPHATES. MITSCHERLICH (202).

P_2O_5 in Manure. Grams.	Dry Matter produced. Grams.	Crop calculated from formula. Grams.	Difference.	Difference × probable error.
0·00	9·8 ± 0·50	9·80		
0·05	19·3 ± 0·52	18·91	− 0·39	− 0·8
0·10	27·2 ± 2·00	26·64	− 0·56	− 0·3
0·20	41·0 ± 0·85	38·63	− 2·37	− 2·8
0·30	43·9 ± 1·12	47·12	+ 3·22	+ 2·9
0·50	54·9 ± 3·66	57·39	+ 2·49	+ 0·7
2·00	61·0 ± 2·24	67·64	+ 6·64	+ 3·0

this method of treatment since it gives a constant independent of the yield and having a definite mathematical meaning.

The various factors we shall have to study are: (1) oxygen supply, (2) light, (3) temperature, (4) water supply, (5) food supply, (6) harmful factors. We must also distinguish between their effect on the three stages of the plant's life, germination, active growth and maturation.

The first five factors must all be present, or growth will not go on; an insufficiency of any one will operate as a limiting factor and put an end to increased growth. Any injurious substance will act as shown in Fig. 2 (p. 23).

Oxygen.—The supply of oxygen to the leaves and stem is always sufficient under agricultural conditions, but the supply to the root and especially to the seed may often be inadequate. This is commonly brought about by the presence of too much water in the soil, by too compact a condition of the soil, or by excess of clay, whereby the perviousness is diminished. On the other hand, if the soil is too loose plants fail to get a proper root hold or a proper water supply.

Light.—H. T. Brown and Escombe (60) have shown that ordinary daylight is more than adequate for the purpose of assimilation, and can be reduced to one-twelfth without any ill-effect. It thus appears that the plant is adapted to the worst light conditions it is likely to find. Whether, however, growth would be as good in this diminished illumination has not been shown; the experience of nurserymen indicates that it is not. Only those rays (chiefly red) absorbed by chlorophyll are effective. The light penetrating the smoky atmosphere of towns appears to have lost much of its activity, whilst light that has passed through a green leaf is practically useless for vegetation. Thus one crop will not grow in the shade of another: a dense crop such as oats, wheat or maize shuts off the supply of light for smaller weeds, and effectually prevents their growth, "smothering

them," in the language of the farmer. This is often the cheapest way of cleaning weedy land. A newly-mown lawn is yellowish if the grass has been allowed to grow rather long, while the interior of a compact tree like the beech is leafless. Forestry practices afford other illustrations; young woods are planted densely in order that the stems of the trees may be kept free from branches and the timber free from knots; later on, however, more light is desirable; heavy thinning of an oak, or beech, forest a few years before the final felling much increases the amount of growth. F. C. Schübeler (252) maintained that the extension of the hours of daylight during summer in northern latitudes more than counterbalanced the low temperatures, and actually shortened the time between sowing and harvest; Wille, however (309), has critically examined the evidence and finds nothing to support this view, all observed differences being readily explained by differences in variety of crop, or in local conditions of soil and climate.

Many years ago Siemens (265) pointed out the advantages of artificial light for greenhouse work, but no method has yet come into practice.

Temperature.—Fig. 1*b* shows the general relationship between temperature and plant growth. The gradient of the curve is at first very steep, a slight temperature increase producing a marked increase of growth; above a certain temperature (which varies somewhat with the conditions) the rate of growth falls off; at higher temperatures the plant suffers, the various processes no longer work harmoniously, and the protoplasm loses efficiency till finally the plant dies.

For purposes of crop production the temperature range is limited by certain secondary effects. If the temperature is too low a purplish pigment appears in the leaf, and the plant grows so very slowly that it is liable in its early stages to succumb to insect pests, such as wireworms, and in its later stages to be cut down by autumn frosts before it has had time to ripen; if, on the other hand, the temperature is too high, the plant becomes taller than usual, less robust and, when much water is also supplied, liable to all the fungoid pests that give so much trouble in commercial greenhouses. Only over a comparatively restricted range of temperature is it possible to obtain the compact sturdy habit aimed at by the grower. This favourable range has not as yet been correlated with other properties of the plant and has to be discovered empirically; it is, on the whole, lower for the seedling than for the growing plant, but it is highest for the period of maturation. It varies for different crops: wheat requires a cool time for sowing but a hot time for ripening, barley requires a cool and oats a still cooler time

throughout. It varies even for different varieties of the same crop; plant breeders are continually trying to evolve strains suited to particular temperature ranges, *e.g.*, wheats have been bred at Ottawa to ripen in the northern parts of Canada. During the course of the twenty-four hours the temperature may exceed the favourable limit for growth, even in our own climate. F. Darwin (77) has obtained some remarkable curves showing that the growth of vegetable marrows is often inversely proportional to the temperature. In hot, dry climates overheating is a very real danger, against which provision has to be made.

Water.—The relationship between the amount of growth and the supply of water is shown by Hellriegel's experiments (128, Table V.) with barley grown under favourable conditions in sand cultures.

TABLE V.—GROWTH OF BARLEY WITH VARYING SUPPLY OF WATER. HELLRIEGEL (128).

Amount of water	5	10	20	30	40	60	80
Dry matter in grain, grams	nil	·72	7·75	9·73	10·51	9·96	8·77
Dry matter in straw, grams	·12	1·89	5·50	8·20	9·64	11·00	9·47
1 grain weighed, mgms.	—	23	35	36	34	32	32

100 represents the amount of water required to saturate the sand.

The yield rises as the water increases up to a certain point and then it falls off because the excess of water reduces the air supply for the roots. In natural soils a further complication sets in when too much water is present: certain reduction products are formed by bacteria in absence of air and have a direct toxic action on the plant.

Determinations have several times been made of the amount of water transpired for every unit of dry matter formed in the plant under particular conditions. It is not supposed that there is any direct causal relationship between the two quantities, nor is there any definite ratio, the amount of water transpired increasing with the temperature and to some extent with the water supply, but decreasing as the food supply increases. The relationship between food supply and water requirements is very interesting and is readily explained. The amount of soluble nutrient salts a plant takes up, and presumably also the concentration of the cell sap, increases with the concentration of these salts in the surrounding medium. But as the concentration of the cell

sap increases so its vapour tension decreases and the amount of water lost by evaporation decreases also.[1]

Lawes at Rothamsted (163) found that about 250 units of water were transpired for every unit weight of dry matter formed; Hellriegel at Dhame (128) obtained higher results, 300-350, Wollny at Munich still higher, 600-700 (318), and Leather at Pusa (167) the highest of all. The effect of variations in water and food supply was also studied by Hellriegel, and more recently by von Seelhorst at Göttingen (256-260), who more than any one else has worked at the various water relationships of plants. His results with oats are given in Table VI.:—

TABLE VI.—EFFECT OF VARYING WATER SUPPLY[2] AND FOOD SUPPLY ON THE WATER REQUIREMENTS OF OATS. VON SEELHORST (258).

	Dry matter produced, grams.			Total water required, grams.			Water required per gram of dry matter.		
	Soil moist.	Soil moister.	Soil still moister.	Soil moist.	Soil moister.	Soil still moister.	Soil moist.	Soil moister.	Soil still moister.
No manure	39·6	48·8	52·6	10·215	15·245	16·290	259·9	312·9	307·1
Complete manure	49·9	86·7	95·1	11·170	20·490	23·030	225·1	236·8	231·6

Similar results have been obtained by Wilfarth (Table VII.), (308), with sugar beets grown in pots of soil containing known but varying amounts of nitrate:—

TABLE VII.—EFFECT OF VARYING FOOD SUPPLY ON THE WATER REQUIREMENTS OF SUGAR BEET. WILFARTH.

Nitrogen supplied, grams	·42	1·26	2·10	2·94	3·36	3·78
Weight of dry matter produced, grams	23·0	73·9	96·5	132·4	167·6	188·8
Water transpired, grams	13100	34570	39420	55190	62600	72280
Stated as inches of rain	3·6	9·4	10·7	15·8	17·0	19·6
Water used per gram of dry matter formed	569	468	409	417	374	383

[1] Fitting (97) has shown that the osmotic pressure of the sap of desert plants is extremely high; the vapour tension is therefore correspondingly low and the plant requires remarkably little water. A different result, however, was obtained by Livingstone (177).

[2] The variations in water supply are:—

	May 5-May 12.	May 12-June 1.	June 1-July 21.
Soil moist	54·4	54·4	44·8
Soil moister	59·2	64·0	59·2
Soil still moister	64·0	73·6	73·6

where 100 = saturation of the soil.

Two deductions may be drawn: (1) water is economised by increasing the food supply; (2) the total amount of water required during the growing season may be greater than is supplied by the rain, in which case the balance must be otherwise provided, or the food cannot be utilised.

Over large areas of the world the rainfall is insufficient, and recourse is had to irrigation. In endeavouring to ascertain the best way of irrigating crops, two considerations have to be kept in view: (1) Excessive watering has secondary injurious effects on the soil, such as the deterioration of the physical condition, the accumulation of alkali salts, or the formation of toxic reduction products; (2) the requirements of the plant are not always the same, more water being needed during the period of active growth than during germination or ripening. Much more work is required from the physiological side before definite rules could be laid down. Wheat would form a suitable plant for study, since it is the crop most commonly grown on irrigated land. In the meantime, experiments like those conducted by the Punjab Irrigation Department[1] have shown that the cultivator everywhere tends to take too much water, with loss not only to others on the same irrigation system, but also to himself.

The amount of water in the soil has a marked effect on the character of the plant, the time of ripening, and the composition of the grain. As the water supply increases, so the extent of the leaf surface increases; while a diminished water supply is met by a smaller leaf surface, admitting of less transpiration. Thus on moist soils—clays and loams—the plants usually have large wide leaves and grow to a considerable size, whilst on the drier sands the vegetation is narrow leaved and more stunted. A copious water supply leads to a more protracted growth and to a retardation of the ripening processes; indeed in very wet districts grain-crops are grown only with difficulty, if at all, because ripening may be so long delayed that frosts intervene and damage the crop.

Water supply and temperature are the two chief factors determining the distribution of crops. In the warm dry eastern counties crops are grown for seed; great quantities of wheat and barley are grown in Norfolk, Suffolk, and the Isle of Thanet; mangold seed and turnip seed is produced in East Kent. Wetter districts are more favourable for swedes and oats; very wet districts for grass. The warm, moist

[1] These and similar experiments are discussed by A. and G. L. C. Howard in *Wheat in India: Its Production, Varieties, and Improvement* (Imperial Department of Agriculture, India, 1909).

south-west of Cornwall is very favourable for early vegetables, cabbage, cauliflower, etc., whilst the cooler Lothians are well suited to potatoes. It is possible by suitable operations to modify somewhat both the temperature and the water content of the soil, and so to make the soil conditions rather more favourable for any particular crop.

Food.—The food of plants, or rather the raw material out of which food is synthesised, consists of carbon dioxide, water, oxygen, and suitable compounds of nitrogen, phosphorus, sulphur, potassium, calcium, magnesium, iron, and, apparently, manganese, silicon, sodium. We have already considered the first three; it remains only to be said that the amount of carbon dioxide in the air is subject to slight variations which may be a factor of importance in crop production. Brown and Escombe (62) found that the amount varied at Kew from 2·43 to 3·60[1] volumes per 10,000 volumes of air, the average being 2·94. Taking the month of July as an example the following average values were found:—

Year.	1898.	1899.	1900.	1901.
CO_2 in 10,000 volumes of air .	2·83	2·88	2·86	3·11

It is highly probable that the plant as a whole would respond to variations of this order, making greater or less growth as the amount of carbon dioxide rises or falls.

Nitrogen.—Of all the nitrogen compounds yet investigated nitrates are the best, and, in natural conditions, probably the only nitrogenous food for non-leguminous plants. The seedling still drawing its sustenance from the seed lives on other compounds: H. T. Brown (63) found that asparagine was the most effective nutrient for the detached embryo of barley, followed by other relatively simple substances like nitrates, glutamic and aspartic acids, ammonium sulphate, etc., the more complex substances being less useful. The experimental study of the nitrogen nutrition of adult plants is complicated by the difficulty of growing plants under sterile conditions and thus obviating the decompositions effected by bacteria; much of the earlier work is vitiated by this circumstance. Later work has satisfactorily shown that ammonia is readily assimilated from solutions of ammonium sulphate, if the concentration is not too high; but even 0·1 per cent. was found injurious by Mazé (196). Krüger (157) concludes that ammonium sulphate is less beneficial than sodium nitrate for mangolds, both compounds are equally useful for oats, barley and mustard, while ammonium sulphate is better for potatoes. Hutchinson and Miller (140)

[1] Only on one occasion was so high a number obtained.

found that peas assimilate nitrates and ammonium salts equally well, while wheat showed a decided preference for nitrates.

None of these preferences has been correlated with any other property of the plants, nor is it easy to explain the fact, on which all experimenters agree, that plants fed on ammonium salts contain a higher percentage of nitrogen than those fed on nitrates (Table VIII.):—

TABLE VIII.—PERCENTAGE OF NITROGEN IN DRY MATTER OF PLANTS.

	Fed on nitrates.	Fed on ammonium salts.	Observer.
Maize . . .	3·17	3·43	Mazé (196 and 197)
Mustard . .	2·87	3·48	Krüger (157)
Oats . . .	1·80	2·05	" "
Wheat . .	1·91	2·17	Hutchinson and Miller (140)

The fact indicates that each unit of nitrogen taken up as ammonia is less effective in the growth process than a unit of nitrogen taken as nitrate, and the plants in spite of their high nitrogen content are really *suffering from nitrogen starvation*.

Nitrites are also assimilated so long as the solution is not too concentrated or too acid.[1]

In spite of a considerable amount of work it is not known whether other nitrogen compounds are assimilated by plants. That many other compounds serve as nitrogen nutrients even without the intervention of bacteria seems to be certain (141), but it has never been shown whether assimilation of the compounds as a whole takes place, or whether there is decomposition at the surface of the root. Most of the supposed assimilated compounds are as a matter of fact more or less easily hydrolysable, or otherwise decomposable, with formation of ammonia, and the decomposition will obviously proceed as fast as the ammonia is removed by the plant. The two factors that determine how far a given compound serves as a nitrogen nutrient are: (1) the ease with which it splits off ammonia, (2) the effect on the plant of the other decomposition products: if these happen to be toxic the whole process stops as soon as they have sufficiently accumulated.

The normal nitrogenous food of plants is, however, a nitrate, and there is a close connection between the amount supplied and the amount of plant growth which is well shown in Hellriegel and Wilfarth's (130) experiments (Table IX.).

[1] See Perciabosco and Rosso, *Staz. Speriment. Agrar. ital.*, 1909, xlii., 5.

TABLE IX.—EFFECT OF NITROGENOUS FOOD SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL.

Milligrams of nitrogen supplied .	0	56	112	168	280	420
Dry matter in crop, grams . .	·742	4·856	10·803	17·528	21·289	28·727
Increased yield for each extra 56 mgms. nitrogen	—	4·114	5·947	6·725	1·880	2·975
Grain, per cent. of dry matter in crop	11·9	37·9	38	42·6	38·6	43·4
Weight of one grain, mgms. . .	19·5	30	33	32	21	30

The figures are plotted in Fig. 3. Similar results are obtained on the field plots at Rothamsted (Table X.).

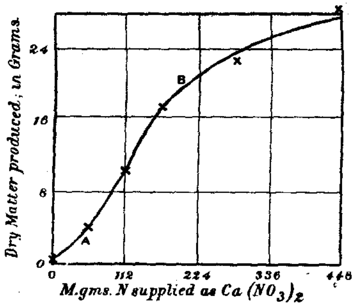

FIG. 3.—Effect of Nitrogenous Food Supply on the Growth of Barley. (Hellriegel.)

TABLE X.—BROADBALK WHEATFIELD, AVERAGE YIELDS, FIFTY-SIX YEARS, 1852-1907.

	Plot 5.	Plot 6.	Plot 7.	Plot 8.
Nitrogen supplied in manure, lb. per acre . .	0	43	86	129
Total produce (straw and grain), lb. per acre .	2315	3948	5833	7005
Increase for each 43 lb. nitrogen	—	1633	1885	1172

The increasing effects produced up to a certain point by successive increments of nitrogen may be due to the circumstance that the additional nitrate not only increases the concentration of nitrogenous food in the soil, but also increases the amount of root, *i.e.*, of absorbing surface, and of leaf, *i.e.*, assimilating surface. The process thus resembles autocatalysis, where one of the products of the reaction acts as a catalyser and hastens the reaction. The increase does not go on indefinitely because some limiting factor steps in.

The effect of nitrogen supply on the grain is very marked. In Table IX. it is seen that the grain formed, when nitrogenous food is

wholly withheld, is only two-thirds of the normal weight per individual. The first addition of nitrate causes a marked rise in the weight per grain and the proportion of grain to total produce, but successive additions show no further rise. Indeed other experiments prove that excess of nitrogenous food causes the proportion of grain to fall off somewhat. The leaf and the general character of growth are affected to a much greater extent. Nitrogen starvation causes yellowing of the leaf, especially in cold spring weather, absence of growth, and a poor starved appearance generally: abundance of nitrogen, on the other hand, leads to a bright green colour, to a copious growth of soft, sappy tissue, liable to insect and fungoid pests (apparently because of the thinning of the walls and some change in composition of the sap) and to retarded ripening: the effects resemble those produced by abundant water supply. A series of plants receiving varying amounts of nitrate are thus at somewhat different stages of their development at any given time, even though they were all sown on the same day, those supplied with large quantities of nitrate being less advanced than the rest. If they could all be kept under constant conditions till they had ripened this difference might finally disappear, but in crop production it is not possible much to delay the harvest owing to the fear of damage by autumn frosts, so that the retardation is of great practical importance. Seed crops like barley that are cut dead ripe are not supplied with much nitrate, but oats, which are cut before being quite ripe, can receive larger quantities. All cereal crops, however, produce too much straw if the nitrate supply is excessive, and the straw does not commonly stand up well, but is beaten down or "lodged" by wind and rain. Swede and potato crops also produce more leaf, but not proportionately more root or tuber, as the nitrogen supply increases; no doubt the increased root would follow, but the whole process is sooner or later stopped by the advancing season—the increased root does in fact follow in the case of the late-growing mangold. Tomatoes, again, produce too much leaf and too little fruit if they receive excess of nitrate. On the other hand, crops grown solely for the sake of their leaves are wholly improved by increased nitrate supply: growers of cabbages have learned that they can not only improve the size of their crops by judicious applications of nitrates, but they can also impart the tenderness and bright green colour desired by purchasers. Unfortunately the softness of the tissues prevents the cabbage standing the rough handling of the market.

Three cases are illustrated in Table XI.: wheat shows increases in straw greater than those in grain as the nitrogen supply is increased;

white turnips show increases in leaf greater than those in root, but mangolds show substantially the same increase both in leaf and root, because their growing period is so much longer than that of the other crops, continuing until the end of October.

TABLE XI.—EFFECT OF VARYING SUPPLY OF NITROGENOUS MANURE ON THE GROWTH OF CROPS. ROTHAMSTED.

Nitrogen in manure, lb. per acre.	Wheat, 1000 lb. per acre (1852-1864).		Nitrogen in manure, lb. per acre.	White Turnips, 1000 lb. per acre (1845-1848).		Nitrogen in manure, lb. per acre.	Mangolds, 1000 lb. per acre (1906-1910).	
	Grain.	Straw.		Roots.	Leaves.		Roots.	Leaves.
none	1·06	1·86	none	18·37	6·05	none	11·84	2·55
43	1·68	3·03	47	22·18	9·63	86	40·12	8·51
86	2·18	4·28	137	22·96	13·78	184	65·67	13·88
129	2·27	4·78	—	—	—	—	—	—
172	2·29	5·22	—	—	—	—	—	—

The actual increase of growth brought about by successive increments of nitrogeneous food depends on the amount of water and other nutrients, on the temperature, and so on; any of these may act as limiting factors. Table XII. shows the crops obtained on some of the Rothamsted mangold plots; in one case the supply of potassium is so small that it becomes the limiting factor, in the other sufficient potassium is supplied.

TABLE XII.—INFLUENCE OF POTASSIUM SALTS ON THE ACTION OF NITROGENOUS MANURES. ROTHAMSTED.

	Average weights, Mangolds, 1906-1910.					
	Roots, 1000 lb. per acre.			Leaves, 1000 lb. per acre.		
Insufficient potassium (Series 5) .	11·97	14·68	18·62	2·59	7·25	7·75
Sufficient potassium (Series 4) .	11·84	40·12	65·67	2·55	8·51	13·88
Nitrogen supplied in manure, lb. per acre	—	86[1]	184[2]	—	86[1]	184[2]

The effect of varying water supply is more conveniently studied in pot experiments than in the field, since any comparison between yields in wet and dry seasons is complicated by the great differences in temperature conditions. Tucker and von Seelhorst (257) put up three series of soil pots in which the water was kept at a definite

[1] From 400 lb. ammonium salts.

[2] From 400 lb. ammonium salts and 200 lb. rape cake.

amount; one was just moist, another moister, and a third still moister. These were then each subdivided into three others, one receiving no nitrogen compounds, another one dose, and the third two doses. Oats were sown in all nine sets with results that are given in Table XIII.:—

TABLE XIII.—INFLUENCE OF WATER SUPPLY ON THE EFFECTIVENESS OF MANURES. VON SEELHORST AND TUCKER (257).

DRY WEIGHT OF OAT CROP.

	Nitrogen Series.			Increased Crop for	
Manuring.	KP.	KPN.	KP_2N.	1st Increment of N.	2nd Increment of N.
I. Moist soil[1]	67·5	68·5	68·5	1·0	0
II. Moister soil	83·6	93·4	94·0	9·8	·6
III. Wettest soil	99·5	119·5	135·0	20·0	15·5

K = 1 gram of K_2O as K_2CO_3 per pot; P = 1 gram of P_2O_5 as $Ca(H_2PO_4)_2$ per pot; N = ·5 gram of N as $NaNO_3$ per pot.

	Phosphate Series.				Increased Crop for		Increase for Complete Manure.
Manuring.	None	KN.	KNP.	KN_2P.	1st Increment of P.	2nd Increment of P.	KNP.
I. Moist soil[1]	41·5	38·5	68·5	79·2	30·0	10·7	27
II. Moister soil	47·2	40·0	93·4	108·0	53·4	14·6	46·2
III. Wettest Soil	68·5	63·5	119·5	127·5	56·0	8	51

When only little water is present the added ·5 gram of nitrogen is without effect, the supply in the soil being sufficient for the crop needs: the water and not the nitrogen is the limiting factor. When more water is added the plant can make more growth, and can therefore utilise more nitrogen: the added ·5 gram now raises the crop by 10 grams. Again, however, the water supply sets a limit, and the second ·5 gram of nitrogen is without effect. When a liberal supply of water is added the first ·5 gram of nitrogen gives 20 grams of crop, double the previous increment; but even this does not represent the whole possibility, for the second ·5 gram of nitrogen gives a still further increase of 15·5 grams.

The results of the phosphate series are somewhat different in detail,

[1] The moist soil contained 14·35 per cent. of water (41·6 per cent. of saturation), the moister soil 15·41 per cent. at the beginning, increasing to 18·43 (51·7 per cent. of saturation) as the experiment proceeded, and the wettest soil, 16·44 per cent. at the beginning, increasing to 22·59 per cent. (63·7 per cent. of saturation).

but not in principle. The first dose of P_2O_5 in the dry soil gives an increased crop, and so does the second, the first not having been large enough; in the wetter soil, however, the increase is much larger. There is a still further increase in the wettest soil, but less than before, some other limiting factor now coming in.

These relations are shown in the curves of Fig. 4, the ordinary

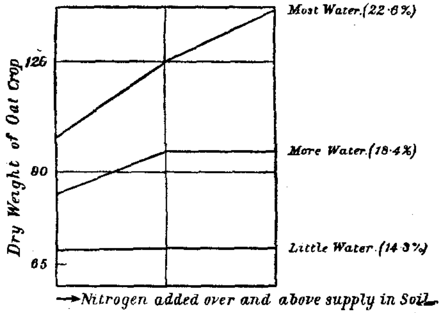

FIG. 4.—Influence of Water Supply on the Effectiveness of Manures. (Von Seelhorst and Tucker.)

series expressing the operation of a limiting factor; they would more properly be expressed by a surface. From the practical point of view the important result is that a given increase in the food supply may produce no increased growth, small increase, or a larger increase, according to the extent of the water supply.

Phosphorus.—Phosphates are by far the most efficient phosphorus foods known for plants. The relationship between phosphorus supply and growth has been measured by E. A. Mitscherlich (p. 24) in a series of experiments on oats grown in sand with each of the three calcium phosphates. For equal weights of the three salts the relative efficiencies corresponded with the basicity; for equal weights of P_2O_5, however, the values were 2·66 : 2·31 : 1·65. This was in sand cultures; in soils different efficiencies were found: thus for the mono-phosphate the values were:—

Sand.	Soil 1.	Soil 2.	Soil 3.
2·66	1·80	1·74	2·40

The effect of a phosphate on the crop is twofold. In the early stages of growth it promotes root formation in a remarkable way. So long ago as 1847 Lawes (160) wrote: "Whether or not superphosphate of lime owes much of its effect to its chemical actions in the soil, it is

certainly true that it causes a much enhanced development of the *under-ground* collective apparatus of the plant, especially of *lateral* and *fibrous* root, distributing a complete network to a considerable distance around the plant and throwing innumerable mouths to the surface". Dressings of phosphates are particularly valuable wherever greater root development is required than the soil conditions normally bring about. They are invaluable on clay soils, where roots do not naturally form well, but, on the other hand, they are less needed on sands, because great root growth takes place on these soils in any case. They are used for all root crops like swedes, turnips, potatoes, and mangolds, and also for shallow-rooted crops with a short period of growth, like barley. Further, they are beneficial wherever drought conditions are likely to come on, because they induce the young roots to grow rapidly into the moister layers of soil below the surface; probably, as Hall has suggested, this explains the marked effect of superphosphate on wheat in the dry regions of Australia.

Later on in the life of the plant phosphates hasten the ripening processes, thus producing the same effect as a deficiency of water, but to a less extent; for this reason they are applied to the wheat crop in some of the northern districts of England to bring on the harvest a few days earlier and obviate risk of loss by bad weather. The northern limit of growth of several crops may in like manner be extended. This ripening effect is well shown on the barley plots at Rothamsted; crops receiving phosphates are golden yellow in colour while the others are still green.

But these effects, important as they are, are nothing like as striking as those shown by nitrogen compounds. There is no obvious change in the appearance of the plant announcing deficiency or excess of phosphate[1] like those changes showing nitrogen starvation or excess; the hastening of maturity is only seen when there is a control plot unsupplied with phosphates and does not even lead to an increase in the proportion of grain borne by the plant. On the Rothamsted plots supplied with nitrogen and potassium compounds, but no phosphate, the grain formed 44·9 per cent. of the total produce during the first ten years of the experiment (1852-1861), and almost exactly the same proportion (44·7 per cent.) during the fifth ten years (1892-1901) when phosphate starvation was very pronounced. Even in sand cultures the difference is not very marked, Hellriegel (131) grew barley with varying supplies of phosphate with results given in Table XIV. In absence of phosphate no grain was formed; when a little was added grain formation pro-

[1] Barley grown in water cultures without phosphorus compounds acquires a red colour in the stem, but this is not commonly seen in the field.

ceeded normally, and the resulting grain was nearly full weight per individual; as the phosphate supply increased the percentage of grain increased, but soon reached a maximum beyond which it would not go.

TABLE XIV.—EFFECT OF VARYING PHOSPHATE SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL (131).

Weight of P_2O_5 supplied, mgms. per pot	0	14·2	28·4	56·8	85·2	113·6	142	213	284
Weight of dry matter in crop, grams per pot	1·856	8·254	12·613	19·505	19·549	20·195	18·667	17·785	31·306
Grain, per cent. of dry matter	—	22·4	31·8	38·4	41·6	43·8	41·3	40·1	43·4
Weight of one grain, mgms.	—	27	29	38	34	41	38	30	34

It is in the total growth of straw and of grain that the effect of phosphate is manifested as shown in Table XV.:—

TABLE XV.—RESULTS OF WITHHOLDING PHOSPHATES, POTASSIUM COMPOUNDS, AND NITROGEN COMPOUNDS FROM BARLEY. HOOS FIELD EXPERIMENTS, ROTHAMSTED.

		Yield of Grain, 1000 lb. per acre.						
Plot.		5 years, 1852-56.	5 years, 1857-61.	10 years, 1862-71.	10 years, 1872-81.	10 years, 1882-91.	10 years, 1892-1901.	10 years, 1902-11.
7	Dung	2·31	2·78	3·00	2·88	2·66	2·56	2·50
A 4	Complete manure (salts of NH_4, K, and P)	2·47	2·71	2·67	2·34	2·24	2·02	2·25
A 3	No phosphates	2·27	1·71	1·99	1·68	1·38	1·26	1·23
A 2	No potassium	2·42	2·70	2·76	2·29	2·01	1·63	1·81
O 4	No nitrogen	1·86	1·57	1·39	·98	·92	·74	·94

		Yield of Straw, 1000 lb. per acre.						
Plot.		5 years, 1852-56.	5 years, 1857-61.	10 years, 1862-71.	10 years, 1872-81.	10 years, 1882-91.	10 years, 1892-1901.	10 years, 1902-11.
	Dung	2·82	3·15	3·35	3·37	3·28	3·35	3·54
A 4	Complete manure (salts of NH_4, K, and P)	3·29	3·17	3·14	2·63	2·61	2·36	2·83
A 3	No phosphates	2·86	2·03	2·20	1·75	1·64	1·56	1·75
A 2	No potassium	3·21	3·03	3·07	2·30	2·20	1·90	2·16
O 4	No nitrogen	2·03	1·58	1·42	·95	·94	·90	1·39

These results are plotted in Fig. 5. The effect of phosphate starvation shows itself in depressing the yield of straw and of grain, the straw being the first to suffer. Potash starvation takes longer to set in, not because potassium is less necessary but because the soil contains

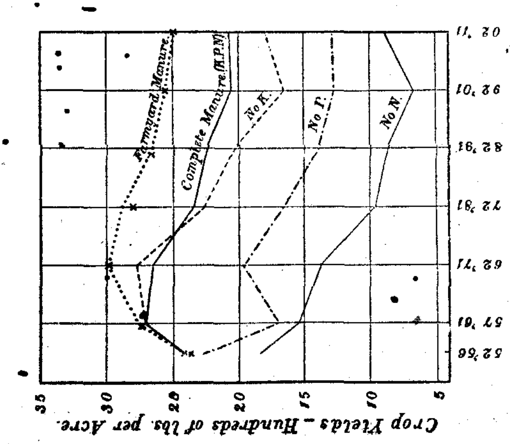

FIG. 5.—Effect on Yield of Grain of withholding various Nutrients from Barley. (Hoos Field, Rothamsted.)

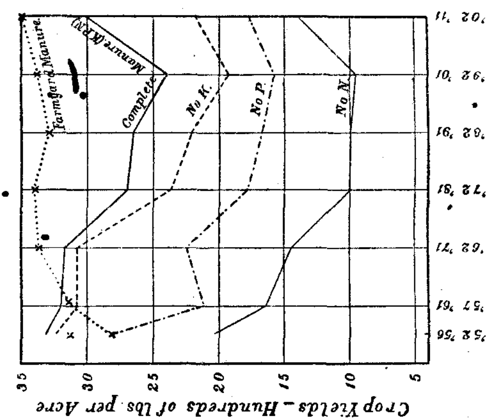

FIG. 5A.—Effect on Yield of Straw of withholding various Nutrients from Barley. (Hoos Field, Rothamsted.)

a larger quantity; it also affects the straw first. Nitrogen starvation sets in at once, rapidly bringing both grain and straw down to a very low level.

It is difficult to get behind these effects and ascertain their causes. The function of phosphoric acid in the cell is not easy to discover; even when the problem is reduced to its simplest state by experimenting with spirogyra in culture solutions little more has been ascertained than that phosphates are wanted for mitotic cell division, doubtless because phosphorus is a constituent of the nucleus, and also for the normal transformations of starch. Loew (181) found that fat and albumin accumulated in absence of phosphates, but the colour was yellow and there was no cell division; as soon as a trace of potassium phosphate was added, however, energetic cell division took place. Reed (236) showed that starch was formed in absence of phosphorus, but did not change to sugars; erythrodextrin was formed instead and also cellulose.

The effects of phosphates in raising the quality and feeding value of the crop are very great. The most nutritious pastures in England and the best dairy pastures in France are those richest in phosphates. Paturel[1] has also shown that the best wines contain most P_2O_5 (about 0·3 gram per litre), the second and lower qualities containing successively less. Further, when the vintages for different years were arranged in order of their P_2O_5 content a list was obtained almost identical with the order assigned by the wine merchants.

This close connection between cell division and phosphate supply may account for the large amount of phosphorus compounds stored up in the seed for the use of the young plant, and also the relatively large amounts of phosphate taken from the soil during the early life of the plant.

Potassium.—Hellriegel has shown (Table XVI.) that equivalent

TABLE XVI.—EFFECT OF POTASSIUM SALTS ON THE GROWTH OF BARLEY. HELLRIEGEL (131).

Mgms. of K_2O per pot	0	23·5	47	70·5	94	188	282
Dry matter formed when—							
KCl was given	2·271	5·414	9·024	9·963	15·322	21·246	24·417
K_2SO_4	2·549	5·140	5·283	13·363	14·768	21·593	23·774
KNO_3	—	4·552	6·621	9·949	14·576	21·499	24·206
[2] KH_2PO_4	—	4·687	6·346	9·931	12·377	17·171	—
K_2HPO_4	—	—	6·684	—	11·736	20·255	—
Average	2·410	4·948	6·791	10·801	13·755	20·357	24·132

[1] *Bull. Soc. Nat. Agric.*, 1911, p. 977.

[2] Lupines, however, could not tolerate the acid condition set up when the monophosphate was supplied (p. 138 in (130)).

amounts of the soluble compounds of potassium have practically all the same nutritive value.

The effect of potassium compounds is more localised than that of phosphates, so that potash starvation can be more readily detected. The colour of the leaf becomes abnormal; the potash-starved grass plots at Rothamsted have a poor, dull colour, as also have the mangold plots; the leaves also tend to die early at the tips. The most striking effect, however, is the loss of efficiency in making starch, pointed out long ago by Nobbe (215); either photosynthesis or translocation—it is not yet clear which—is so dependent on potassium salts that the whole process comes abruptly to an end without them. Mangolds, sugar beets, potatoes, and other sugar- and starch-forming crops reduce their production of sugar with decreasing potassium supply even before the leaf area has been diminished. Thus, in the mangold experiments of Table XII. (p. 34), 7255 lb. of leaf give rise to 14,684 lb. of root where potash food is deficient, while very little more leaf, 8508 lb., give rise to nearly three times as much root, 40,128 lb., where more potassium salts are supplied. The harmful effect of potash starvation on carbohydrate production does not seem to be the result of a pathological condition of the chloroplastids. Reed found that they remained normal for two months and even increased in numbers in potash-starved algæ.

A second effect is on the formation of grain; unlike phosphates and nitrates, potassium compounds have a very marked effect on the weight of the individual grains, as may be seen by comparing Table XVII. with the corresponding Tables IX. (p. 32) and XIV. (p. 38); indeed to withhold potash is the surest way of producing stunted grain. These stunted grains are often sterile on the potash-starved grass plots at Rothamsted.

TABLE XVII.—EFFECT OF POTASSIUM SALTS ON THE DEVELOPMENT OF BARLEY. HELLRIEGEL (131).

K_2O supplied, mgs.	0	23·5	47	70·5	94	188	282
Dry matter in crop, grams	2·271	5·414	9·024	11·636	15·302	20·946	29·766
Grain, per cent. of dry matter	—	4·8	21·5	27·2	30·1	38·5	42·7
Weight of one grain, mgs.	—	5	9·5	13	17	26	34

Lastly, the tone and vigour of the plant are very dependent on the potassium supply; potash-starved plants are the first to suffer in a bad season, or to succumb to disease. The Broadbalk wheat plots receiving potassium salts give conspicuously better results than the others whenever the year is unfavourable to plant growth; taking the yield on

the unmanured plot as an index of the character of the season, we obtain the following results for a series of good and of bad years respectively:—

TABLE XVIII.—YIELD OF WHEAT IN THOUSAND POUNDS PER ACRE. ROTHAMSTED.

	Plot No.	In Nine Bad Seasons.[1]		In Nine Good Seasons.[1]	
		Grain.	Straw.	Grain.	Straw.
Unmanured	4	·55	·87	·88	1·08
Insufficient potash	11	1·06	1·86	1·51	2·20
Sufficient potash	13	1·70	3·02	1·98	3·16
Percentage increase due to potash	—	60·3	62·3	31·1	43·6

In the bad years the average rainfall was 32·55 inches (harvest years, September-August), while in the good years it was 27·10 inches; the badness of the season may be connected with the high rainfall and corresponding low temperature. Similar results are obtained, however, if other unfavourable conditions set in.

The improvement in tone is well exemplified by the power of resisting disease. At Rothamsted the potash-starved wheat is badly attacked by rust, the mangold leaves by *Uromyces betæ*, and the grass by various other fungi, while the surrounding plots, equally liable to infection, remain healthy. Growers of tomatoes under glass have found that the ravages of various fungi and of eelworms are much diminished by manuring the plants with potassium salts.

Next to the sugar-producing plants, the leguminosæ seem to stand most in need of potassium salts. The potash-starved grass plots at Rothamsted contain notably less clover than those fully manured, the actual depression fluctuating according to the season. Some of the weeds, especially the sorrel, require a good supply of potash.

In absence of potassium salts mitotic cell division does not go to completion; Reed observed that the cell and nucleus both elongate, but actual division does not occur (236).

It is not at present possible to say whether all these phenomena are different manifestations of one and the same specific action of potassium in the plant, or whether there are several different causes at work.

Sodium can partially, but not completely, replace potassium as a

[1] The bad years were 1867, '71, '72, '75, '76, '77, '79, '86, '88; the good years were 1868, '69, '70, '81, '83, '85, '87, '89, '91.

plant nutrient; it thus delays the setting in of potash starvation, but will not keep it off altogether. Hellriegel (131) found that sodium salts always gave increases in crop even when potassium salts were present in quantity.

TABLE XIX.—EFFECT OF SODIUM SALTS WITH SMALL AND WITH LARGE AMOUNTS OF POTASSIUM SALTS ON THE GROWTH OF BARLEY. HELLRIEGEL (131).

K_2O supplied, mgs.	0	94	188	282	376
Dry matter produced when sodium salts added	4·925	23·019	32·278	36·535	38·270
Dry matter produced when no sodium salts added	2·658	15·638	29·724	34·897	36·281
Difference due to sodium salts	2·267	7·381	2·554	1·638	1·989

Breazeale (52) has more recently obtained similar results in water cultures. It is well ascertained in farming practice that sodium salts can be used with great effect as manures wherever there is any deficiency of potash in the soil.

Lithium salts, on the other hand, have a toxic action on plants. Gaunersdorper's older experiments (100) have been confirmed by J. A. Voelcker (290), who found that amounts of the chloride, sulphate, or nitrate, corresponding to ·00375 per cent. of the metal were distinctly injurious to wheat; smaller amounts, however, appeared to cause an increased growth.

Cæsium salts are less harmful (189, 290).

Calcium is an essential plant food, the function of which was first carefully studied by von Raumer (233), but has not yet been satisfactorily cleared up. Nothing can be inferred from the fact that, like potassium, it occurs more in the leaf than in the seed. It certainly gives tone and vigour to the plant; gypsum is used in alkali regions to counteract the harmful effects of excessive amounts of saline matter in the soil. It also appears to stimulate root production: if calcium is withheld from water cultures the size of the root is much reduced.

Its most remarkable effects are seen in water cultures. Curiously enough, single salts of potassium, magnesium, sodium, &c., are toxic to plants, while a mixture of salts is not. Calcium salts are by much the most powerful reducers of this toxic effect. Thus Kearney and Cameron (147) found that a root of *Lupinus albus* was just killed when immersed in ·00125 N magnesium sulphate solution (7 parts per 100,000), but the effect was modified by added salts, as shown in Table XX.:—

TABLE XX.—EFFECT ON VARIOUS SALTS IN REDUCING THE TOXICITY OF $MgSO_4$. KEARNEY AND CAMERON (147).

	Alone.	$+MgCl_2$ (·0025 N).	$+Na_2CO_3$ (·0025 N).	$+Na_2SO_4$ (·01 N).	+ NaCl (·015 N).	$+CaCl_2$ (·2 N).	$+CaSO_4$ (Saturated).
Strength of $MgSO_4$ that just kills the root .	·00125 N	·000625 N	·00125 N	·00375 N	·0075 N	·2 N	·6 N

Hansteen (see 214) found that the toxic effect of potassium salts used singly was overcome even when so little lime was added that the ratio $\frac{CaO}{K_2O} = \frac{1}{840}$. Osterhout found (223) that *Vancheria sessilis* lived for three weeks in distilled water, but was killed in a few minutes by $\frac{3}{32}$ N NaCl, and in a few days by ·0001 N NaCl; yet the toxic effect even of the stronger solution disappeared on adding one gram-molecule of $CaCl_2$ for every 100 gram-molecules of NaCl. Magnesium chloride and sulphate, potassium chloride and calcium chloride were also toxic when used singly, but in admixture they formed a nutrient medium in which the plant grew normally and developed fruit even when $\frac{3}{32}$ N NaCl was also present.

It is also found that calcium and magnesium ions diffuse out from the plant cell more rapidly into solutions of single sodium or potassium salts than into pure water and very much more rapidly than into solutions of calcium salts. Niklewski (214) found the amounts of CaO and of MgO diffusing out of cut pieces of beet to be:—

	Mgs. per 500 cc. of solution.	
	CaO.	MgO.
Beet placed in distilled water	5·3	4·1
Beet placed in ·05 N KCl	33·4	23·8
Beet placed in ·05 N NaCl	32·1	20·8
Beet placed in ·05 N NH_4Cl	29·2	21·3

These facts can be explained on Loeb's theory (179) that life phenomena depend upon a balanced adjustment between a number of "metal proteids" in the tissues, *i.e.*, compounds of proteins with calcium, magnesium, sodium, etc. If the circumambient solution contains only one of these metallic ions it must soon displace others in the tissues and upset the balance with fatal consequences.

Other facts are less easy to explain, such as Grafe and Portheim's

observation that the toxic effects of a single salt fail to appear, or are much delayed, when sugar is supplied.[1]

Reed found that mitotic division proceeded normally in absence of calcium, but the new transverse cell wall was either incomplete, or entirely absent.

Strontium salts not only have no nutritive value, but in Loew's experiments on algæ (182) they injuriously affected the chlorophyll bodies, causing loss of starch-making power and finally death.

Magnesium, like phosphorus, finally moves to the seed, and is thus in contrast with calcium and potassium which remain behind in the leaf or the straw. Willstätter has shown (310) chlorophyll to be a magnesium compound, an observation that accounts for the unhealthy condition of the chlorophyll bodies, and the final etiolation of magnesium-starved plants. Further, magnesium seems to be necessary for the formation of oil, the globules being absent from algæ growing in solutions free from magnesium salts; oil seeds are richer in magnesium than starch seeds. An excess of magnesium salts produces harmful effects which, as we have seen, can be lessened by addition of calcium salts; Loew indeed considers (180) that plants require a definite $\frac{CaO}{MgO}$ ratio in their food, but neither Gössel[2] nor Lemmermann[3] could obtain evidence of any such necessity.

Iron.—For some reason difficult to explain the formation of chlorophyll is absolutely dependent on the presence of a trace of some ferric salt, although iron does not enter into the composition of chlorophyll. So little is wanted that iron salts never need be used as manures, excepting for water or sand cultures.

Manganese is considered by Bertrand to be a constituent of oxidases, and, therefore, necessary to the plant; minute traces only are required, larger quantities being harmful. A number of field experiments[4] have shown that manganese salts may act as manures. Bertrand classes them as "engrais complémentaires" (35).

Chlorine does not appear to be necessary to the plant, indeed Knop grew even the halophytes without it. Chlorides are always present in rain water in ample amount to supply any trace that might be needed. In small doses iodides and fluorides have been found, according to Japanese experiments, to produce beneficial results (183 and 278).

[1] *Bied. Zentr.*, 1908, xxxvii., 571. [2] *Bied. Zentr.*, 1904, xxxiii., 226.

[3] *Landw. Jahrbuch*, 1911, xl., 175 and 255.

[4] Numerous Japanese experiments are recorded in the *Bull. Coll. Agric.*, Tokyo, 1906, *et seq.* (210), and Italian experiments in the *Studi e Ricerche di Chimica Agraria*, Pisa, 1906-8; pot experiments have also been made by J. A. Voelcker at the Woburn Experiment Station.

Sulphur is probably an essential food constituent, but is wanted only in small quantities. Sulphates are present in rain and in soil, but further additions in manure have been found by Dymond (93) to be useful for heavy crops rich in protein, although they were not needed for cereals or permanent pastures.

Silicon does not seem to be essential, but it occurs to so large an extent in some plants that it is not likely to be wholly useless. Wolff and Kreutzhage (315) found that soluble silicates increased the yield of oats in water cultures and also the proportion of grain, behaving in their opinion much like phosphates. Certain of the Rothamsted plots are treated with sodium silicate, and marked crop increases are obtained on the phosphate-starved plots (Table XXI.). Hall and Morison (119) conclude that silicates act by causing an increased assimilation of phosphoric acid by the plant, the seat of action being in the plant and not in the soil.

TABLE XXI.—EFFECT OF SILICATES ON THE GROWTH OF BARLEY, 1864-1904. ROTHAMSTED.

	Yield of dressed Grain, bushels.		Yield of Straw, cwts.		Ratio Total Grain / Straw	
	Without Silicate.	With Silicate.	Without Silicate.	With Silicate.	Without Silicate.	With Silicate.
Nitrate only	27·3	33·8	16·2	19·8	85·1	86·6
Nitrate + phosphate	42·2	43·5	24·6	25·8	87·2	85·8
Nitrate + potassium salts	28·6	36·4	17·9	21·7	80·6	85·0
Nitrate + phosphate + potassium salts	41·2	44·5	25·3	27·6	82·7	82·1

Absence of Injurious Substances.—We have seen that many salts have a toxic effect if given alone to the plant, but for our purpose we need consider only those causing injury in presence of other compounds. Two cases arise in practice: some substances are injurious in small quantities, others only in excess.

Substances Injurious in Small Quantities: Acids.—Cultivated plants will usually not grow in too acid or too alkaline a medium, but prefer something more nearly neutral. In water cultures it is necessary to begin with a faintly acid solution because of the formation, as growth proceeds, of sodium and potassium carbonates (see p. 119): in soils, however, certain changes set in that not only obviate the need for acidity but necessitate the presence of calcium carbonate.

The unsuitability of the atmosphere of industrial towns has been

traced in part to the presence of acids, which affect the leaves as well as the roots. Wieler[1] found that assimilation of carbon dioxide was profoundly modified by sulphur dioxide, most injury being done in moist weather when the stomata were more widely opened and the gas could readily enter the leaf tissues. Crowther and Ruston (72) obtained the following yields from pots of Timothy, showing that acid water gradually kills the plant :—

TABLE XXII.—EFFECT OF ACID RAIN-WATER ON THE GROWTH OF TIMOTHY GRASS. CROWTHER AND RUSTON (72).

Weight of dry matter obtained when plants were regularly watered with :—

	Country rain neutralised.	Leeds rain (acid).	Solution of sulphuric acid, parts per 100,000 of water :—					
			1	2	4	8	16	32
1st crop, 1908	28·0 gms.	23·8 gms.	30·5	28·7	28·8	24·8	23·8	14·1
2nd crop, 1909	24·9 „	17·5 „	18·2	17·8	10·0	8·2	1·8	0
3rd crop, 1910	14·7 „	6·6 „	12·0	8·0	3·9	3·7	0	0

Metallic Salts.—Complaints are sometimes made by farmers in mining districts that their crops suffer damage from the waste products —generally metallic salts—turned into the streams from the works, especially where the water is wanted for irrigation, or where, as in Japan, rice is grown in the marshes. A vast number of experiments have shown that copper salts are extraordinarily toxic in water cultures or where they actually come into contact with the plant, even the minute trace sometimes present in distilled water being harmful. This property finds useful application in removing algæ from water and in killing weeds. For example, a 3 per cent. solution of copper sulphate is sprayed over cornfields in early spring at the rate of fifty gallons per acre to destroy charlock (*Brassica sinapis*), one of the most troublesome weeds on light soils. The solution adheres to the rough horizontal leaves of the charlock and kills the plant, but runs off the smooth vertical leaves of the wheat without doing much damage. Even the insoluble complex copper salt present in Bordeaux mixture, and sprayed on to fruit trees to kill fungoid pests, was found by Amos (2) to retard assimilation of carbon dioxide by the leaf.

Copper salts do not appear to be anything like so toxic in the soil as in water culture.

It is often asserted that any toxic substance must, at proper dilu-

[1] *Bied. Zentr.*, 1908, xxxvii., 372.

tions, act as a stimulant to plants; with copper sulphate, however, Miss Brenchley (54) could obtain no evidence of increased growth in water cultures at any dilution, even down to one part in ten millions of water, although the toxic effect was always shown. The pot experiments of Russell and Darbishire lead to the same conclusion (239).

Zinc salts have often been made the subject of investigation because the older pot experiments were conducted in zinc vessels. In a recent critical summary Ehrenberg (94) concludes that zinc salts are always toxic when the action is simply on the plant, but they may lead to increased growth through some indirect action on the soil itself.

Ferrous Salts.—Ferrous salts are toxic and are commonly regarded as one cause of the sterility of badly aerated soils.

Most metallic salts appear to be toxic except those of the few metals required for nutrition. No unexceptionable evidence of a stimulating effect on the plant has yet been obtained, although certain effects may be produced in the soil leading to increased growth (see p. 114).

Whenever infertility is traced to any of these metallic salts a good dressing of lime is found to be an effective antidote.

Various Other Substances.—Sulphuretted hydrogen is extremely toxic, so also is ammonium sulpho-cyanide which, in the early days, used to cause trouble as an impurity in ammonium sulphate made from gas liquor. It is rarely, if ever, found now. Toxic nitrogen compounds include nitrites, which have to be removed from synthetical calcium nitrate used for manure, the complex cyanides associated with commercial cyanamide, and ammonium salts at too high a concentration. None of these, however, is for long harmful in the soil, since all are fairly rapidly converted into nitrates. Perchlorates are harmful and used sometimes to occur in sodium nitrate, but they are now carefully removed. Arsenates are poisonous and form the basis of most weed killers.

Substances Injurious in Large Quantities. Soluble Salts.—In many arid districts the soil contains such large quantities of sodium and potassium salts that the soil water is too concentrated to permit of plant growth. Sodium carbonate not infrequently occurs and directly poisons the plant. Such soils are called alkali soils: they may be treated with gypsum, or, still better, carefully washed with irrigation water.

Calcium carbonate is sometimes considered harmful because plants are liable to chlorosis on chalky soils. It is equally probable, however, that the general soil conditions are responsible for the disease (see p. 122).

Magnesium Salts.—The toxicity of magnesium salts was discovered

by Tennant in the eighteenth century in studying the harmful effects of certain limestones found near Doncaster (281). Cases are reported by Loew where excess of magnesia in the soil has caused infertility; none, however, have fallen under the writer's observation in this country. As already stated, any injurious effect can be overcome by treatment with lime.

Effects of Salts on Germination.—Salts generally cause a retardation in the rate of germination; some of Guthrie and Helms' (115) results are given in Table XXIII. Sigmund has studied the effects of a very large number of substances (266). The technical interest in the work lies in the fact that seeds are sometimes treated with antiseptics before sowing in order to kill any spores of disease organisms, and, moreover, certain soluble salts—artificial manures—are often put into the soil about the same time as the seeds are sown.

TABLE XXIII.—EFFECT OF SOLUBLE SALTS ON GERMINATION. GUTHRIE AND HELMS (115).

	Sodium chloride, per cent.		Sodium carbonate, per cent.		Sodium chlorate, per cent.		Arsenic trioxide, per cent.	
	Barley.	Rye.	Barley.	Rye.	Barley.	Rye.	Barley.	Rye.
Germination affected	0·10	0·10	0·25	0·25	0·005	0·004	0·6	0·20
„ prevented	0·25	0·40	0·60	0·50	0·007	0·006	—	0·4
Growth affected .	0·10	0·15	0·15	0·25	0·003	0·002	0·05	0·15
„ prevented .	0·20	0·20	0·40	0·40	0·006	0·004	0·10	0·30

When a solution comes in contact with a seed it does not necessarily enter as a whole. Adrian Brown (57) has shown that the barley seed is surrounded by a membrane which has the remarkable property of keeping out many dissolved substances and allowing the water only to pass in, so that the solution loses water and becomes more concentrated. A number of substances can, however, pass through the membrane, and to these H. E. and E. F. Armstrong (3, 4) have applied the term Hormones. In general they have no great affinity for water; in the Armstrongs' nomenclature they are *anhydrophilic*: they pass into the cell and there disturb the normal course of events. Ammonia, toluene, ether, chloroform, are all highly effective hormones readily entering the cells of seeds, leaves, etc., and hastening the normal sequence of processes.

Stimulation of Plants by Electricity and by Heat.

The Electric Discharge.—It has often been stated that an electric discharge increases the rate of growth of plants either by direct action

on the plant, or by indirect action in the soil. As far back as 1783 the Abbé Bertholon (34) constructed his *electro-végétomètre*, a kind of lightning conductor that collected atmospheric electricity and then discharged it from a series of points over the plant. The view that atmospheric electricity is an important factor in crop growth has always found supporters in France. Grandeau (112) stated that plants protected from atmospheric electricity by a wire cage made less growth than control plants outside.

Instead of relying on atmospheric electricity Lemström (171) generated electricity on a large scale and discharged it from a series of points fixed on wires over the plant. This method has recently been much developed at Bitton, near Bristol, on the electrical side by Sir Oliver Lodge, on the botanical side by J. H. Priestley, and on the practical side by J. E. Newman.

In J. H. Priestley's experiments (230) the rate of respiration of the plant was much increased under the influence of the discharge provided ozone was not formed in appreciable quantity. The amount of transpiration increased so that more water was needed, there was also a marked acceleration in the ripening of the crop. The following crop increases are said to have been obtained :—

Wheat, 29 per cent.	Strawberries, 25 per cent.
Carrots, 50 per cent.	Beets, 33 per cent.

Various Rays.—Recent experiments of Miss Dudgeon are quoted by Priestley to show that the rays of the Cooper-Hewitt mercury vapour lamp have a very stimulating effect, accelerating germination and increasing growth to a remarkable extent. Priestley found that the rays from a quartz mercury vapour lamp were harmful at close range, whilst farther off they stimulated growth. There is great scope for work in this direction ; the problem is of great economic importance, because of the enhanced market value of early crops.

Effect of Heat.—Molisch (203) has shown that perennial plants steeped in hot water towards the close of their deepest period of rest come at once into activity. His hypothesis is that the "rest" required by plants is of two kinds, the *freiwillig* rest due to external conditions and therefore capable of being shortened, and the *unfreiwillig* rest inherent in the nature of the plant. Parkinson (225) has tested the method with satisfactory results ; spirea, rhubarb, seakale, etc., steeped for twelve hours in water at 95°, at the end of November, or early in December, made rapid growth when subsequently forced.

CHAPTER III.

THE CONSTITUTION OF THE SOIL.

It is well known that only the top six or eight inches of the soil is suited to plant life, and that the lower part, or subsoil, plays only an indirect part in plant nutrition. We shall, therefore, confine our attention almost exclusively to the surface layer.

The soil was in the first instance derived from rocks, partly by disintegration and partly by decomposition. The fragments split off were sooner or later carried away by water and deposited at the bottom of a river or sea. There they mingled with residues of living organisms which have subsequently played an important part in the history of the soil as its chief source of calcium carbonate and calcium phosphate. In course of time the material accumulated to considerable depths; then, as the result of some earth change, the water retreated leaving the deposited material as dry land or rock. No sooner was this exposed to the air than it began once again to undergo disintegration and erosion. Air, water and frost all played a part in the disintegration process; water and sometimes ice have acted as transporting agents. For immense ages the particles have been subjected to these actions, and the fact that they have survived shows them to be very resistant and practically unalterable during any period of time that interests us. Reference to Table LVI., page 140, shows that the particles in the surface soil which have been exposed to weathering ever since the soil was laid down, and in some cases to cultivation for some hundreds of years, are almost indistinguishable in size from those in the subsoil which have been protected from all these changes.

However, the soil particles are not wholly unalterable. The rain water and its dissolved carbonic acid exert a slight solvent action, and the soil water always contains small amounts of calcium and magnesium compounds, silica and other substances in solution. Each individual particle only loses a very minute amount of substance to the soil water, and its life is extraordinarily long; nevertheless dissolution is perpetually taking place. The surface soil contains less of the smallest, and, therefore, most easily attacked, particles than the subsoil.

In any region where the rainfall and temperature conditions are favourable, soil rapidly covers itself with vegetation; even a bare rock surface is not without its flora. The first vegetation must obviously have obtained its mineral food from the dissolved material of the soil particles, but when it died and decayed all the substances taken up were returned to the soil, so that subsequent vegetation has food from two sources: from the substances dissolved direct out of the soil particles during the life of the plant, and from those dissolved out at earlier times and taken up by previous races of plants. Thus in the natural state, and where the vegetation is not removed, the mineral plant food can be used over and over again and indeed tends to accumulate as fast as it is extracted from the soil particles by the rain water.

The plant, however, returns to the soil more than it takes away; during its life it has been synthesising starch, cellulose, protein and other complex, unstable and endothermic bodies, much of which fall back on the soil when it is dead. This added organic matter introduces a fundamental change because it contains stored-up energy; the difference between the soil as it now stands and the original heap of mineral matter is that the soil contains sources of energy while the mineral matter does not. Hence it soon becomes the abode of a varied set of organisms, drawing their sustenance and their energy from the accumulated residues, and bringing about certain changes to be studied later; some, as we shall see, are capable of fixing gaseous nitrogen and so increasing the supply of protein-like compounds, whilst others can assimilate carbon dioxide.

Thus the complex that we speak of as the soil consists of four parts:—

1. The mineral matter derived from rock material, which constitutes the frame-work of the soil and is in the main unalterable, but it contains some reactive decomposition products.

2. The calcium carbonate and phosphate (the latter being usually in much smaller amount), and organic matter derived from marine or other organisms deposited simultaneously with the soil.

3. The soil water, a dilute solution of carbonic acid containing small quantities of any soluble soil constituent.

4. The residues of plants that have grown since the soil occupied its present position, consisting of the mineral plant food taken up from the soil water and of part of the complex organic matter. As the source of energy this may be regarded as the distinguishing characteristic of soils.

These four constituents are invariably present, but not in the same

proportion; their relative abundance affords the basis on which soils are classified. From the agricultural point of view we thus have: (*a*) mineral soils consisting mainly of rock material, subdivided into sands, loams and clays; (*b*) calcareous soils containing notable amounts of chalk or limestone; (*c*) alkali soils rich in soluble, saline matter; (*d*) acid humus or peat soils where much organic matter has accumulated in absence of calcium carbonate; (*e*) neutral humus soils where much organic matter has also accumulated, but in presence of sufficient calcium carbonate to prevent acidity.

By far the greater proportion of agricultural soils belong to the first group.

The Mineral Portion of the Soil.

By the method of mechanical analysis described in the appendix the particles of soil can be sorted out into fractions, each falling within certain specified limits of diameter; those adopted in Great Britain are given in Table XXIV.:—

TABLE XXIV.—SIZE AND AVERAGE COMPOSITION OF FRACTIONS OBTAINED BY MECHANICAL ANALYSIS. HALL AND RUSSELL (124).

Name of fraction.	Average diameter of particles, mm.	Average composition.							Remarks.
		SiO_2.	Al_2O_3.	Fe_2O_3.	CaO.	MgO.	K_2O.	P_2O_5.	
Fine gravel	above 1	94·4	3·0	2·1	·4	·8	·6	·06	
Coarse Sand	1 to 0·2	93·9	1·6	1·2	·4	·5	·8	·05	
Fine sand	0·2 to 0·04	94·0	2·0	1·2	·4	·04	1·5	·02	
Silt	0·04 to 0·01	89·4	5·1	1·5	·8	·3	2·3	·03	
Fine silt	*0·01 to 0·002*	*a* 84·1	7·2	2·6	1·1	·2	3·2	·1	Fraction ·01 to ·005 m
		b 64·3	19·3	7·6	2·2	·4	5·3	·4	Fraction ·005 to ·002 m
Clay	below 0·002	*c* 53·2	21·2	13·2	1·6	1·[illegible]	4·9	·4	From fertile soils.
		d 49·0	29·8	13·1	1·5	1·0	3·4	·7	From less fertile soils.

The fractions fall into two broad groups: the sand, silt, and the coarser part of the fine silt are mainly silica, while the clay[1] and some of the fine silt are complex silicates containing much iron and alumina. The silica fractions do not represent distinct substances, the lines are all artificial and merely divide up into a convenient number of groups a mixture that shows a perfect graduation from an upper down to a lower limit. So far as is known all these groups are chemically inert. The clay fraction, on the other hand, stands out in

[1] It is unfortunate that no distinct word has been generally adopted for this fraction; "clay" already stands for a particular mineral and also for a heavy soil.

sharp contrast both in composition and in chemical and physical properties. At least two groups of clay were recognised by Hall and Russell, one associated with fertile soils, the other with less fertile soils. The analytical figures throw very little light on the constitution of the clay beyond showing that it is not a simple silicate expressible by a definite chemical formula. Other methods have proved more fruitful, and two in particular: (1) the study of the absorption by soils of various ions—NH_4, K, PO_4, and others—from their aqueous solutions; (2) van Bemmelen's successive extraction of soils and clays with acids of increasing concentration. These we must study in some detail.

Mention has already been made of the fact that soils precipitate salts of ammonium, potassium and phosphates as well as organic compounds form their solutions. Liebig (175) regarded this property as purely physical, but Way (298) showed in a classical research that it is really chemical. Starting with Thompson's observation (283) that calcium sulphate goes into solution when ammonium sulphate solution is shaken with soil, he showed in the first instance that the amount of base dissolved out is equivalent to the amount of ammonia fixed, and thus established the chemical nature of the change. His next experiments were to discover the particular constituent of the soil with which the reaction took place; he found it was neither the calcium carbonate, the sand, the undecomposed rock however finely ground, nor the organic matter.[1] The active constituent was in the clay, but it formed only part of the clay, and moreover it lost its power on ignition. No known simple silicates showed these properties, but he prepared a number of "double silicates" of lime and alumina, of soda and alumina, etc., that did; thus they reacted, like clay, with ammonium salts to form an almost insoluble double ammonium silicate and a soluble calcium salt, and also, like clay, they lost this property after ignition. Although he did not establish the existence of such double silicates in soil, their resemblance to the reactive constituent in the soil was so close that he considered himself justified in assuming their presence.

Further experiments by A. Voelcker (287, 288) and others have shown that the same change takes place when ammonium sulphate is added to the soil as manure, an insoluble nitrogen compound[2] being formed which remains in the soil, while the calcium sulphate

[1] It was subsequently shown by König (153) that soil organic matter has a marked power of absorbing ammonia from ammonium sulphate.

[2] This insoluble substance does not seem to be an ordinary ammonium compound since it is not completely decomposed on distillation with magnesia. [Russell (242).]

washes out in the drainage water. Potassium sulphate reacts in the same way, the potassium being precipitated and an equivalent amount of calcium going into solution. Potassium phosphate undergoes a more complete precipitation, since calcium phosphate is insoluble. The precipitated potassium compound dissolves somewhat in water, but it has no definite solution pressure, instead the amount of potassium dissolving increases with the amount present. It can also be decomposed by sodium salts; hence addition of sodium sulphate to the soil increases the amount of soluble potassium ions and to this extent acts like a dressing of potassic manure. Magnesium salts have a similar effect, and, like sodium salts, lead to an increase in the amount of potassium available for the crop. Some of Lawes and Gilbert's results (166) are given in Table XXV.:—

TABLE XXV.—EFFECT OF SODIUM AND MAGNESIUM SULPHATES IN INCREASING THE SUPPLY OF POTASH TO THE PLANT. LAWES AND GILBERT (166).

	Ammonium Salts only.	Ammonium Salts+Superphosphate.	Ammonium Salts+Super. +Sulphate of Sodium.	Ammonium. Salts+Super. +Sulphate of Magnesium.	Ammonium Salts+Super. +Sulphate of Potassium.	Ammonium Salts+Super. +Sulphates of Sodium, Magnesium, and Potassium
1852-1861.	Plot 10.	Plot 11.	Plot 12.	Plot 14.	Plot 13.	Plot 7.
K_2O in ash of straw, per cent. . .	18·8	14·8	20·1	22·0	24·1	23·7
K_2O in ash of grain, per cent. . .	33·9	31·7	32·8	32·6	32·9	32·9
Weight of K_2O in ten whole crops, lb. .	300	309	454	498	532	560
1862-1871.						
K_2O in ash of straw, per cent. . .	14·5	14·1	17·2	18·5	25·0	24·6
K_2O in ash of grain, per cent. . .	34·1	32·1	33·3	33·1	33·5	33·4
Weight of K_2O in ten whole crops, lb. .	240	260	378	391	552	530
Total amount of K_2O taken by crop during the twenty years, lb. .	540	569	832	889	1084	1090

In the twenty years the sodium sulphate has enabled the plant to take up an additional 263 lb. of K_2O, whilst the magnesium sulphate has furnished it with an extra 320 lb. over and above what the crop on Plot 11 can get.

The interaction between ammonium sulphate and the clay has been found by Hall and Gimingham (121) to follow the ordinary law of mass within a certain restricted range of concentration, but, according to the old experiments of Weinhold (300) and the recent ones of Cameron and Patten (67), not over a wider range.

Some ions, however, are not precipitated in the soil, including CO_3, SO_4, NO_3, Cl, Mg, Ca, Na;[1] these are, therefore, the chief constituents of drainage water.

Organic substances, particularly those of high molecular weight, are also withdrawn from their solutions, but the reaction is apparently of a different type, since nothing appears to be given up from the soil in exchange. The result is of extreme importance; practically the whole of the organic matter added to the soil by plant residues or manure remains near the surface unless carried down mechanically by some agency such as earthworms. Even when heavy dressings of dung are annually supplied at Rothamsted there is after fifty years no appreciable enrichment of the subsoil in nitrogen (Table XXVI.).

TABLE XXVI.—NITROGEN IN BROADBALK WHEAT SOILS, 1893.
Per cent. of dry soil.

	Annual Dressing of Manure.					
	Unmanured.	Dung, (200 lb. N).	Minerals only.	Minerals + 200 lb. Ammonium Salts, (43 lb. N).	Minerals + 400 lb. Ammonium Salts, (86 lb. N).	Minerals + 600 lb. Ammonium Salts, (129 lb. N).
Top 9 in.	·0992	·2207	·1013	·1107	·1222	·1188
9 to 18 in.	·0730	·0767	·0739	·0720	·0681	·0752
18 to 27 in.	·0651	·0656	·0645	·0628	·0583	·0630
			lb. per acre.			
Top 9 in.	2572	5150	2630	2870	3170	3080
9 to 18 in.	1950	2050	1970	1920	1820	2010
18 to 27 in.	1820	1830	1800	1750	1630	1760
Nitrogen supplied in Manure in the 50 years	None	10,000	None	2150	4300	6450

The purification of sewage by land treatment affords further illustrations of the absorptive power of soil for organic matter.

Van Bemmelen has shown that there is a close parallelism between the various interchanges and absorptions shown by the soil and

[1] From the time of Aristotle it has been known that sea water could be "desalted" by filtering through sand or soil. But it has recently been shown by Von Lippmann and Erdmann (*Chem. Zeit.*, 1911, xxxv., 629) that the water first running through the sand filter is not desalted sea water, but displaced water. When this has all gone the salt water runs through unchanged.

those shown by colloids; the only hypothesis capable of explaining the observed facts is that some of the constituents of the soil, and especially of the clay, are colloidal.

This view is fully borne out by van Bemmelen's fractionations of soil and of clay. By successive extraction with acids of increasing concentration van Bemmelen found (22) two distinct groups of silicates in the Dutch alluvial soils, one soluble in dilute hydrochloric acid in which the ratio $\frac{\text{molecules of } SiO_2}{\text{molecules of } Al_2O_3} = 3$ to 5,[1] the other soluble only in hot, strong sulphuric acid in which the ratio is approximately equal to 2. Other soils of volcanic origin from Java gave up larger amounts of base relative to the silica, but in no case were the ratios constant whole numbers; the alkaline bases showed the same lack of constancy *in their ratios to* Al_2O_3.

TABLE XXVII.—RATIO $\frac{\text{MOLECULES OF } SiO_2}{\text{MOLECULES OF } Al_2O_3}$ EXTRACTED FROM VARIOUS SOILS.
VAN BEMMELEN (22).

Solvent.	Temperature and Time of Extraction.	Alluvial soils, Holland.		Volcanic soils, Java.		Laterite soils, Surinam.
HCl of sp. gr. 1·03	15 mins. at 55°	3·7	5·0	·9	2·1	1·1
HCl of sp. gr. 1·2	1 hour boiling temp.	3·4	4·6	2·2	2·7	1·6
H_2SO_4 conc.	—	2·0	2·4	3·2	2·0	1·6

Alkaline bases extracted from a heavy clay, Surinam.

Solvent.	Temperature of Extraction.	Al_2O_3 dissolved, per cent.	Ratio $\frac{\text{Mols. } SiO_2}{\text{Mols. } Al_2O_3}$	Mols. of bases extracted for 1 mol. of Al_2O_3. CaO.	MgO.	K_2O.	Na_2O.
HCl of sp. gr. 1·03	55°	1·2	1·3	·33	·83	·10	}
HCl of sp. gr. 1·1	100°	3·4	2·7	·05	·32	·08	}
HCl of sp. gr. 1·2	boiling	4·6	2·7	·03	·14	·09	} ·01
HCl of sp. gr. 1·2	,,	2·5	2·7	·03	·10	·10	}
HCl of sp. gr. 1·2	,,	1·9	2·7	·03	·08	·12	}
Conc. H_2SO_4	—	8·8	2·0	·005	·06	·17	·02

Different soils gave up different proportions of alkaline bases, but again without showing definite simple ratios one to another. Detailed studies of clay revealed the presence of chemically unchanged crystals

[1] The higher numbers were obtained from sandy clays and the lower from heavy clays. As the silica was insoluble in the acid it was extracted by digesting the residue for a few minutes at 55° with dilute alkali of sp. gr. 1·04.

of the original silicates and also of easily soluble substances including a fusible group with ratio $\frac{\text{molecules of } SiO_2}{\text{molecules of Al O}}$ varying from 3 to 6, and a silicate resembling kaolin with ratios varying between 2 and 3. The easily soluble material represents the products of weathering since it does not occur in rocks. If it were a definite chemical compound the ratio of its constituents should be constant whole numbers, but this is not the case. It behaves, however, precisely like a solid solution and is therefore regarded by van Bemmelen as an "absorption compound," SiO_2, mAl_2O_3, nFe_2O_3 . . . pH_2O, in which the constituents are not chemically united but are held by the feebler forces manifested by colloids in their attractions one for the other.

The Physical Properties of the Various Fractions.—Serious studies of the soil by competent physicists have scarcely been attempted as yet, and the work hitherto done can only be regarded as preliminary. The fundamental difficulty in applying the ordinary physical methods is to synthesise the soil; numerous studies have been made of the physical properties of sand, silt, clay, etc., considered as separate entities, but no one has worked out the resultant when all the varying grades of sand, silt and clay are intimately mingled, or drawn up a scheme or formula to express the properties of the soil in terms of the mechanical analysis. More useful results are obtained by the method of correlation; soils of known properties are analysed and the results are correlated so far as is possible with the properties; even this method, however, can only be used very crudely, because the physical properties of the soil as a whole cannot at present be expressed by definite numbers. Only a very general summary will therefore be attempted.

The Clay Fraction.—Clay may be regarded as a plastic colloid, but its special properties are only seen when a certain amount of water is present. If it is well rubbed with water it becomes very sticky and absolutely impervious to air or water; it is also highly plastic, and can be moulded into shapes which remain permanent on drying and baking. It shrinks very much on drying and absorbs heat; on moistening again, however, there is a considerable swelling and evolution of heat. The reversibility of the process has been studied by van Bemmelen (20, 25), who has also shown that the rate at which water is lost on drying over sulphuric acid is not essentially different from the rate at which evaporation takes place from a pure water surface under the same conditions. The separate particles of clay are so small that, when placed in water, they assume a state of Brownian movement and sink only very slowly in spite of their high specific gravity. Traces of electrolytes

have a profound effect on these properties; small quantities of acids or salts cause the temporary loss of plasticity, impermeability, and the property of remaining long suspended in water without settling; the clay is now said to be flocculated. The change can be watched if a small quantity of any flocculating substance is added to the turbid liquid obtained by shaking clay with water; the minute particles are then seen to unite to larger aggregates which settle, leaving the liquid clear. There is, however, no permanent change; deflocculation takes place and the original properties return as soon as the flocculating agent is washed away. Alkalis (caustic soda, caustic potash, ammonia and their carbonates) deflocculate clay, causing it to remain suspended in water for long periods. Clay is thus an electro-negative colloid, its reaction probably being conditioned by a trace of potash liberated by hydrolysis. It shows the general properties of electro-negative colloids as elucidated by Schulze (254) and Hardy (125): thus it is flocculated only by a solution containing ions or particles of opposite electrical sign, and the extent of flocculation increases rapidly with the valency and concentration of the ion. No quantitative relationships, however, could be found by Hall and Morison (120).

A remarkable change sets in when clay is heated beyond a certain point, and it permanently loses all its special properties.

These clay properties are of great importance to the fertility of the soil, and no constituent is more necessary in proper proportions, or more harmful in excess. Clay impedes the movement of water in the soil and keeps it in the surface layers within reach of the plant roots, thus making the soil retentive of water. Excess of clay, however, interferes too much with the water movements, making the soil waterlogged in wet weather and parched in dry seasons even though the permanent water level is near the surface; it also impedes the movement of air to the roots and lowers the temperature of the soil. The adhesive properties of clay cause the soil particles to bind together into those aggregates on which "tilth" depends; soil without clay would be very like a sand heap. Here also, however, excess of clay does harm and makes the soil so adhesive that it sticks to the tillage implements and retards their movements; it also tends to form large clods unfavourable to vegetation. These effects are intensified in wet weather; the soil becomes sticky or "poached" and must not be worked or the tilth is injured for a long time. Another effect of a large amount of clay is to make the soil shrink very much on drying, so that large cracks appear in the fields in summer time. These harmful effects are reduced by flocculation effected by dressings of lime or

chalk (which become converted into calcium bicarbonate in the soil) and by organic matter; on the other hand, they are intensified by the deflocculation resulting from the use of alkaline manures like liquid manure, or by sodium nitrate, which leaves a residue of sodium carbonate in the soil. Further, as pointed out above, clay "fixes" and retains the ammonia and potash supplied as manure. In general 8 to 16 per cent. is a satisfactory proportion of clay in a soil where the rainfall is 20 to 30 inches per annum.

Fine silt (0·01 to 0·002 mm. in diameter) has also great water-holding power, and in excessive amounts (above 10 to 15 per cent.) it increases the difficulty of working the soil, especially if much clay is present. It does not possess the marked plastic and colloidal properties of clay and is less altered by lime; indeed no method is known for making it tractable. It is usually less in amount than the clay; certain peculiarities in cultivation are manifested where the reverse obtains, *e.g.*, in the Lower Wealden strata, the Upper Greensand and the Lincolnshire warp lands.

The coarser grade of *silt* (0·04 to 0·01 mm. in diameter) appears to be very valuable, and constitutes 30 to 40 per cent. of many of the loams most famous in the south-east of England for carrying their crops well and not drying out. Light, sandy loams, on the other hand, may contain only 10 to 20 per cent.; some of these are highly fertile, but as a rule they require large dressings of dung, or a situation favourable for water supply. Probably silt plays a very important part in maintaining the even conditions of moisture so desirable for plant growth. It is fine enough to retard, but not to prevent, percolation, and it facilitates capillary movement of water.

Fine sand (0·2 to 0·04 mm. in diameter) forms a considerable fraction —usually 10 to 30 per cent. or more—of nearly all soils. Although its dimensions are relatively large, it still possesses cohesiveness and a tendency to cake together; it has not, however, so great an effect as silt in maintaining a good moist condition. Soils containing 40 per cent. or more of fine sand tend to form, after rain, a hard crust on the surface, through which young plants can only make their way with difficulty until it has been broken by a roller. But they have no great water-holding capacity or retentive power, and are not infrequently described by their cultivators as hungry soils that cannot stand drought. The notoriously infertile Bagshot sands and the barren Hythe beds in West Surrey are largely composed of this fraction, as much as 70 per cent. being sometimes present. In all these cases, however, clay is deficient and the situation is dry; better results are obtained when

the clay exceeds 8 or 9 per cent., or when the water table is near the surface, especially if the amounts of coarse sand and gravel are not too high.

Coarse sand (1 – 0·2 mm. diameter) is perhaps the most variable of all soil constituents in amount, and, as its properties are in many ways the reverse of those of clay, it exercises a very great effect in determining fertility. Through its lack of cohesion it keeps the soil open and friable; in moderate amounts it facilitates working, but in excess it increases drainage and evaporation so much as to interfere seriously with the water-holding capacity of the soil. Many good loams contain less than 4 per cent., and in general strong or tenacious soils contain less coarse sand than one-half the quantity of clay present. When the coarse sand exceeds the clay in amount the soil becomes light, unless of course the clay is above 20 per cent., when the soil must always remain heavy. Not being a colloid, it possesses no power of absorbing water or soluble salts. Soils containing 40 per cent., or more, of coarse sand and less than 5 per cent. of clay are only cultivated where large quantities of dung are available, or where the water supply is exceptionally good. As the amount of coarse sand increases, the soils become less and less suited to cultivation, till finally the sand dune condition is reached.

Fine gravel is not usually present to any great extent, and is of importance only when the coarse sand is already dangerously high. Stones cannot be determined quantitatively by any method of sampling in use, and their effect must be judged by a visit to the field. If they are uniformly scattered through a stiff soil, as in the Clay-with-Flints, they are on the whole beneficial, because they facilitate tillage. Where they form a bed underlying the soil they may do harm by causing over-drainage. Some typical examples are discussed in chapter VI.

Calcium Carbonate.

Calcium carbonate is often present in small amounts only, but it plays a controlling part in soil fertility. It produces both chemical and physical effects. It prevents the formation of cert.in conditions that otherwise tend to arise, conditions that are not yet investigated, but are unfavourable to many agricultural plants and soil micro-organisms. It gives rise to the soluble bicarbonate that flocculates clay, and thus physically improves the soil texture. There is a certain critical stage where comparatively small changes in the amount of calcium carbonate may very materially alter the native flora, the predominant weeds, the

soil micro-organisms, the liability of the plants to disease and the tractability of the land. Soils sufficiently supplied with calcium carbonate stand out in sharp contrast with those containing too little, although they may be of similar composition in all other respects. So great is the effect that the practical man has long since adopted the special term "sour" to describe soil deficient in calcium carbonate, a term we shall find it convenient to retain. Table XXVIII. shows pairs of soils similar in constitution and general external conditions, temperature, water supply, etc., but very different in agricultural value because of their different content of calcium carbonate, one being readily cultivated while the other is wet and sticky, and only suitable for pasture land:—

Table XXVIII.—Effect of Calcium Carbonate on the Texture of Soils.

	Hamsey Green.		Rothamsted.	
	Arable Soil.	Too sticky for Arable.	Arable Soil, Barnfield.	Too sticky for Arable, Geescroft.
Fine gravel	1·7	1·6	2·4	1·8
Coarse sand	5·3	9·5	5·5	4·9
Fine sand	28·7	22·3	20·3	27·8
Silt	26·3	25·4	24·4	25·4
Fine Silt	10·2	9·9	12·7	10·6
Clay	16·4	16·0	22·6	19·0
Loss on ignition	4·8	5·2	4·7	5·1
Calcium carbonate	1·02	·48	3·0	·16

It is impossible to ascertain the amount of calcium carbonate necessary for a soil except by actual field trials: in general, sandy soils require only sufficient to prevent sourness, while clay soils need in addition enough to keep the texture good. Sands well supplied with calcareous water and under ordinary arable cultivation may get along with 0·1 per cent. or even less calcium carbonate, while others that are being heavily dunged respond to dressings of chalk, or ground limestone, even though 0·2 or 0·3 per cent. is already present. It commonly happens that 0·5 per cent. of calcium carbonate proves insufficient for clay soils, and even 1·0 per cent. may not be enough in highly-farmed districts, especially where cattle are fed on the land and tread the soil into a somewhat sticky state. Further increases in calcium carbonate over and above the critical amount are not known to have any effect except to provide a margin of safety.

Calcium carbonate is not a permanent constituent of the soil, but

changes into the soluble bicarbonate and washes out into the drainage water; the average loss per acre per annum throughout England and Wales has been estimated at 500 lb., and at Rothamsted on the arable land at 800 to 1000 lb. (118). The rate of loss is influenced by the treatment, being increased by the use of ammonium sulphate and decreased by dung and by the crop; it is much less on pasture than on arable land. Repeated additions of calcium carbonate to the soil are, therefore, necessary: indeed chalk and lime are among the oldest of manures. Soils lying immediately above chalk and limestone are no exceptions and in wet regions they may become thoroughly decalcified.

On chalk soils the percentage of calcium carbonate may rise very high, and then a wholly new set of properties comes in. It is impossible to draw any exact line showing where these properties begin to appear, but they entirely mask the effects of the silica and silicate particles and obliterate the distinctions between sands, loams, clays. Chalk soils, therefore, form a class by themselves to which the ordinary laboratory methods of analysis and investigation do not apply: unfortunately, appropriate methods have not yet been worked out.

The Soil Water.

The soil retains by absorption and surface attractions some 10 to 20 per cent. of its weight of water, distributed as films over its particles. This water is of obvious importance as the medium through which plants and micro-organisms derive their food, indeed the Whitney school regard it as the culture solution for the plant. Its relationship to the mineral matter is discussed by Cameron (68, 69). Notwithstanding its importance, however, but little is known of it, because of the difficulty of getting it away from the soil. No pressure method has proved successful, but a centrifugal method which, however, has not come into general use, gave the following results (Whitney & Cameron (304)):—

	Soil solution parts per million.				Dry soil parts per million.			
	PO_4.	NO_3.	Ca.	K.	PO_4.	NO_3.	Ca.	K.
Sassafras loam, New Jersey—								
Wheat, good	7·20	7·20	44·40	33·60	1·35	1·35	8·34	6·31
Wheat, poor	7·00	·40	26·90	24·40	1·40	·08	5·38	4·88
Leonardtown loam, Maryland—								
Wheat, good	6·30	1·44	16·20	21·60	1·38	·32	3·56	4·75
Wheat, good	8·40	4·08	21·60	38·40	1·48	·72	3·80	6·75
Wheat, poor	9·75	4·80	8·30	19·25	2·45	1·21	2·12	5·10

Instead of using this method the United States Bureau of Soils investigates the solution obtained by stirring up soil with water, and filtering under pressure through a Chamberland filter. The results (304) are taken to indicate the following as the average composition of the soil water:—

PO_4	NO_3	Ca	K	
7·64	5·47	11·67	22·74	per million of dry soil.[1]

The numerous analyses of land drainage water that have been made in this country and on the Continent throw some light on the composition of the soil solution. As might be expected from the known absorptive properties of clay and of humus, drainage water contains mere traces of NH_4 and PO_4, and only little K; it contains chiefly carbonic acid, SiO_4, Cl, SO_4, NO_3, Ca with some Fe, Mg and Na. Typical analyses are given in Table XXIX. :—

TABLE XXIX.—ANALYSES OF DRAINAGE WATERS FROM CULTIVATED FIELDS: PARTS PER MILLION OF SOLUTION.

	Rothamsted: Broadbalk Field.[2]			Field at Göttingen.[3]	
	No Manure.	Dung.	Complete Artificials.	Highest result.	Lowest result.
	Plots 3 & 4.	Plot 2.	Plot 6.		
CaO	98·1	147·4	143·9	184	157
MgO	5·1	4·9	7·9	46·4	31·3
K_2O	1·7	5·4	4·4	3·7	1·7
Na_2O	6·0	13·7	10·7	—	—
Fe_2O_3	5·7	2·6	2·7	—	—
Cl.	10·7	20·7	20·7	—	—
SO_3	24·7	106·1	73·3	59·2	43·5
P_2O_5	·6	—	1·54	—	—
SiO_2	10·9	35·7	24·7	—	—
N as NH_3	·14	·20	·24	—	—
N as Nitrate	15·0	52·0	32·9	8·2	1·0
Organic matter, CO_2, etc.	67·7	77·3	84·6	—	—
Total solids	246·4	476·0	407·6	—	—

It will be observed that the total concentration of the Rothamsted drainage water varies from ·02 to ·05 per cent.

[1] The Bureau of Soils prefer to express the composition in terms of dry *soil*, rather than in terms of the solution.

[2] A. Voelcker's analyses of five samples collected between 1866 and 1869 (289).

[3] Von Seelhorst's analyses of samples collected weekly, or fortnightly, from a field between August, 1899, and August, 1900 (261).

Organic Matter.

The distinguishing characteristic of soil is that it contains part of the complex material synthesised by plants. This material affords energy to numerous micro-organisms, and is gradually converted by them into simple substances appropriate for plant nutrition. We may look upon its constituents as taking part in a perpetual cycle: in one stage nourishing the growing plant and storing up the energy of sunlight, in the other stage nourishing micro-organisms and liberating energy. In addition, it has important physical effects on the soil. Unfortunately, not much is known of the highly complex components of the plant and even less is known about the important organic substances of the soil. The difficulty of working with insoluble, unstable bodies mingled with twenty times or more their weight of sand, silt and clay has hitherto proved almost insuperable. The ideas current in the text-books go back to the time before organic chemistry arose, and have come down direct from C. Sprengel (269), Mulder (204), and Detmer (85).

We can thus only speak in the most general terms about what is admittedly the characteristic component of soil. Two great groups are to be carefully distinguished: one furnished by recent generations of plants; the other deposited with the soil during its formation, and therefore as old as the soil itself. Unfortunately, no actual method of separation is known, but some idea of the amount and properties of the original organic matter can be obtained from a study of the subsoil at depths below the root-range of plants. Ten feet or more below the surface, sandy subsoils usually contain less than ·01 per cent. of nitrogen and clays less than ·05 per cent., but shales contain more than ·1 per cent. The percentage of carbon fluctuates, but is usually five to ten times that of nitrogen (199). Now these values are about one-tenth to one-fifth of those obtained in the surface soil, so that at the very outside, and assuming there has been no decomposition, not more than 10 to 20 per cent. of the surface organic matter is original.

The organic matter furnished by recent vegetation may roughly be classified as: (1) material that has not yet had time to decompose and still retains its definite cell structure; (2) partially decomposed and still decomposing material; (3) simple soluble decomposition products; (4) plant or animal constituents not decomposable in the soil.

The undecomposed material is important as the reserve supply for the entire chain of reactions to be considered later. It also has a certain mechanical effect in opening up the soil and facilitating aeration,

and drainage, an effect useful on clays but often harmful on sands where these processes already tend to go too far.

The partially decomposed material forms a particularly vague and indefinite group containing all the non-volatile products of bacterial, fungal, enzymic and other actions on the plant residues. It shades off in one direction into the simple soluble decomposition products, and in the other into undecomposed plant fragments, so that it cannot be sharply defined or accurately estimated. A detailed study of the group being thus out of the question, we must ascertain in the first instance what part it plays in determining those relationships between the soil and the living plant that it is our business to study, and then, when we know what to look for, try to discover what constituents are important from our point of view and fix attention on them. For the preliminary inquiries recourse is had to the indirect method of correlation already used in ascertaining the properties of the mineral fractions of the soil. Numerous studies on these lines have proved that this group possesses at least six properties not shown by the undecomposed plant residues:—

1. It gives a dark brown or black colour to the soil.

2. It can withdraw various ions—NH_4, K, PO_4—from their solutions. The experiments of van Bemmelen (19, 21) indicate a complete parallelism with clay in this respect.

3. It causes the soil to puff up, or in the expressive phrase of the German farmer, to "ferment" (*Bodengärung*), and so leads to an increase in the pore space (see p. 104). From this results a marked improvement in the tilth and general mechanical condition. The Rothamsted mangold plots receiving no organic manure, and therefore poor in this group, get into so sticky and "unkindly" a state that the young plants have some difficulty in surviving however much food is supplied, and may fail altogether if bad weather intervenes in the spring (as in 1908 and 1911); the dunged plots which are rich in this group are much more favourable to the plant and never fail to give a crop. But the puffing up or "lightening" may go too far, and sometimes causes much trouble in old gardens that have long been heavily dunged.

4. It increases the water-holding capacity of the soil. The amounts of moisture present in adjacent plots at Rothamsted were:—

Date.	Barley Plots, Hoosfield.		Date.	Mangold Plots, Barnfield.	
	Dung.	Artificial Manures only.		Dung.	Artificial Manures only.
1911.	Plot 7-2.	Plot 4A.	1910.	Plot 2-o.	Plot 4-o.
May 17 . .	21·2	15·8	May 30 .	17·0	12·7
June 8 . .	15·8	10·9	June 4 .	17·9	12·3
September 13 .	6·9	3·8	July 27 .	15·5	12·2
1912.					
February 15 .	21·2	17·7			

The variations in water content follow very closely the variation in the amount of organic matter present. So marked are these physical effects that if 15 or 20 per cent. of organic matter is present in a soil the operation of other factors ceases to count for much, and the distinctions between sands, loams, and clays are obliterated. Thus, much of the famous Red River prairie soil of Manitoba is identical in mineral composition with certain poor infertile wealden soils, but the presence of 26 per cent. of organic matter completely masks the harmful effect of the clay and fine silt. A similar pair of soils, owing their difference in agricultural properties to their different organic matter content, have been analysed by C. T. Gimingham (105):—

TABLE XXX.—EFFECT OF ORGANIC MATTER[1] ON THE TEXTURE OF SOILS.

	Good Texture.	Poor Texture.	Good Texture.	Poor Texture.
	Manitoban Prairies.	Weald Clay.	(Reported by C. T. Gimingham.)	
Fine gravel . . .	—	·5	—	—
Coarse sand . .	1·6	1 to 2	·6	·5
Fine sand . . .	3·8	10 to 12	4·3	8·4
Silt	17·1	20 to 30	11·2	13·8
Fine silt . . .	28·2	25 to 30	28·7	26·5
Clay	23·3	20 to 25	23·8	25·0
Loss on ignition . .	26·3	5 to 8	19·8	14·5

5. It swells when wetted.[2]

[1] Measured by the loss on ignition.

[2] Peat shows this phenomenon in a marked degree, indeed after heavy rainfall inadequately-drained peat bogs may swell so much as to overflow into valleys with disastrous results. After drainage, however, drying and shrinkage set in, followed by a slow but steady erosion as air penetrates into the newly-formed spaces and starts the oxidation processes. When Whittlesey Mere was drained in 1851 a pillar was driven through the peat into the underlying gault, and the top of the pillar was made flush with the surface of

6. Although the group is essentially transitional it has a certain degree of permanency and only slowly disappears from the soil.

The group of substances possessing these properties is generally called "humus," and so long as the word is used in a collective sense as a convenient label it may be retained. But the practice has been responsible for a good deal of loose thinking, because it obscures the fact that the group is an indefinite and complex mixture, and gives instead the impression that it is a single definite substance.

From these half-dozen general properties we may infer that humus is a brown, slowly oxidisable colloid, but unfortunately we cannot get much further. Careful examination of a number of soils in their vegetation relationships has shown that there must be several distinct types of humus, but the laboratory methods are not yet as sensitive as the growing plant and fail to indicate some of the differences. We have to look to field observations for the facts on which to base a scheme of classification, and, unfortunately, these are not yet very numerous.

An admirable series of studies has been made by P. E. Müller (205) of the types of humus occurring in the Danish forests. In beech forests he found two types, which he called *mull* and *torf*, our nearest equivalents being mould and peat. On *mull* the characteristic plants were *Asperula odorata* with its associated *Mercurialis perennis*, *Milium effusum*, *Melica uniflora*, *Stellaria nemorum*, and others, moss being absent. The *mull* itself was only a few inches thick, and was underlain by 1 to 5 feet of loose soil, lighter in colour than *mull*, but almost equally rich in organic matter; still lower came a compact but porous layer of soil. The surface of the soil was covered by a layer of leaves, twigs, etc. Earthworms were numerous throughout; their potent influence in the soil had recently been shown by Darwin (75). Detailed chemical examination was not made: it was shown, however, that *mull* was free from acid and contained about 5 to 10 per cent. of organic matter completely disintegrated and most intimately mingled with the mineral matter.

Torf differed completely. The characteristic plant was *Trientalis europæa* with the associated *Aira flexuosa* and moss, but surface vegetation was not very common. The loose layer of leaves was absent, and the *torf* itself was so tough and compact that rain water could not readily penetrate. Below it was a layer of loose, greyish sand (*blei-*

the soil. So great has been the subsequent shrinkage that over 10 feet of the pillar is now out of the ground, and the process has not yet reached its limit, for a perceptible shrinkage took place during the dry season of 1911.

sand), and lower still a layer of reddish soil (*roterde*), or else a pan (*ortstein*). Practically no earthworms were found in the *torf*, but there were numerous moulds and fungi, *Cladosporium humifaciens* Rostrup and *Sorocybe Resinæ* Fr. being perhaps the commonest.

Torf was acid, contained about 30 per cent. of organic matter not completely disintegrated, nor well mixed with the mineral matter. It was not very favourable to the growth of young trees, and the forest tended to become an open heath as the old trees died.

The distribution of *mull* and *torf* did not seem to be determined by the nature of the soil, or by the amounts of soluble alkali salts or calcium carbonate present, but rather by the nature of the living organisms in the soil. Animals, especially earthworms, gave rise to *mull*, fungi produced *torf*. If the conditions were favourable to earthworms *mull* was therefore found, if not, *torf* was produced. The nature of the vegetation was also a factor: oak only rarely formed *torf* but commonly gave rise to *mull*, at least two varieties of which were observed; pine, like beech, could form either *torf* or *mull*, while *Calluna vulgaris* and *vaccinium myrtillus* generally produced *torf*.

Observation work on similar lines has been carried on in this country by Dr. Moss and other members of the British Vegetation Committee (280). At least three great classes and another two that may be transition forms were recognised:—

1. Dry peat (the German *Trockentorf*) found on heaths in relatively dry regions and on poor sandy soils. It is often only a fraction of an inch in thickness, and is largely formed by lichens and mosses (*e.g. Cladonia rangiferina*, *Polytrichum piliferum*, and others). The dominant plant is *Calluna*. Much of the organic matter of heath soils, however, often consists of undecomposed vegetation, *e.g.* bracken fronds, etc.

2. In wetter districts the layer of peat becomes thicker, and no doubt changes in composition, but it still carries essentially "heath" vegetation, although it shows resemblances to (3).

3. Wet peat (the German *Hochmoor*) formed in wet tracts or regions of high rainfall, and accumulating to so great a depth that it entirely determines the character of the vegetation whatever the underlying rock. It receives no supplies of spring or underground water, and, therefore, no dissolved salts; the drainage water is acid and poor in soluble mineral matter. Two great divisions are recognised: *lowland moors* or mosses, formed in low-lying wet places largely from Sphagum, cotton grass (*Eriophorum*), and *Calluna*; and *upland moors*, formed mainly from *Eriophorum* spp. and *Scirpus caespitosus* in elevated districts of high rainfall.

4. Fen (*Niedermoor* in German, see (299)) formed from a calcicolous vegetation (*Phragmites*, *Cladium*, *Scirpus*, *Carex*, etc.), in presence of calcium carbonate and soluble mineral salts, showing no acid properties and giving alkaline drainage waters.

5. Garr, genetically related to the fen.

Between fen and peat several transition forms have been described by Weber (299) and also recognised in England. Some of our moors are built up on older fens.

Within each of these great classes several subdivisions are recognised, but how far they arise from differences in the organic matter, or from other differences, cannot yet be ascertained. Nor is it known whether any of these classes is identical with the "humus" of grass or arable land. There is no doubt that a close study jointly by a botanist and a chemist would carry the problem much nearer to a solution.

The observations indicate that the mixture we have agreed to call humus does not vary erratically from field to field, but produces much the same effects over any tract where similar soil and climatic conditions prevail. The mixture changes when a new set of conditions occurs, but its general character persists over a certain range and then it merges into another type.

How many such types are recognisable will not be known till many more observations such as the above have been made, but as each type is settled by the ecologist it becomes the business of the chemist to examine the mixture and endeavour to correlate its composition with its properties. Two great divisions of the types can already be recognised: a neutral group commonly spoken of as neutral humus or "mild humus," and a group reacting like an acid (although Baumann (9, 10) could find no evidence that it actually contained an acid[1]), and called "sour humus," acid humus, or by German writers *Rohhumus*.

In order to understand much of the chemical work that has been done, it is necessary to remember that the older chemists regarded humus as a single definite substance, or as a mixture of two or three definite substances. The favourite view was to consider neutral humus as the calcium salt of "humic acid," which could be extracted from the soil by dilute alkalis after preliminary treatment with hydrochloric acid. On acidifying this alkaline extract the "humic acid" came down as a brown colloidal precipitate. Acid humus was the actual humic acid itself. It was further supposed that humic acid could be synthesised

[1] There is no agreement even on this point. Sven Odén (*Ber.*, 1912, xlv., 651-660) has recently made various physical measurements which in his opinion prove beyond doubt the existence of a definite humic acid. See also footnote, p. 72.

by boiling sugar with hydrochloric acid, on the singularly inadequate ground that the product thus obtained is also a brown colloid. Numerous analyses have been made both of the natural and the synthetic "humic acid" some of which are given in Table XXXI.[1]

TABLE XXXI.—ANALYSES OF THE ORGANIC MATERIAL EXTRACTED BY ALKALIS FROM SOIL (OFTEN CALLED HUMUS, SOLUBLE HUMUS, ACTIVE HUMUS, *MATIÈRE NOIRE*, ETC.).

Source.	Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Ash.	Observer.
Arable land	56·3	4·4	36·0	3·3	Calculated ash-free	Mulder (204)
Garden soil	56·8	4·9	34·8	3·5		,,
Pasture land	56·1	5·3	32·5	6·1		,,
Peat	59·0	4·7	3·6	32·7		,,
Rich prairie soil	45·1	3·7	28·6	10·4	12·2	Snyder (267)
Soil never cultivated	44·1	6·0	35·2	8·1	6·6	,,
Cultivated subsoil (*a*)	48·2	5·4	33·2	9·1	4·2	,,
,, ,, (*b*)	50·1	4·8	33·7	6·5	4·9	,,
"Humic acid" from sugar	66·4	4·6	29·0	—	—	Berthelot and André (30-32)
"Humic acid" from compost	53·3	5·6	37·5	3·6	—	Berthelot and André (30-32)

These results are in accordance with the general fact brought out by the field observations, that under similar conditions the humus mixture is tolerably constant, but it is quite clear that each set of soils gives up a different lot of substances to alkalis. Indeed simple variations in the time or the method of extraction cause differences in the results even from the same soil.[2]

The fact that humus is not a definite compound but a complex indefinite colloid was established by van Bemmelen in a remarkable paper

[1] Many partial analyses have been made. Cameron and Breazeale (66) in nineteen samples obtained percentages of carbon varying from 33·3 to 50·1, whilst Hilgard (133) found the nitrogen content to be:—

	Percentage of Humic Acid in the Soil.	Percentage of Nitrogen in the Humic Acid.
Soils of the arid regions (decomposition rapid)	0·20 to 3·0	8·7 to 22·0 (average 15·2)
Soil of the sub-irrigated arid regions	0·36 ,, 2·0	5·4 ,, 10·6 (,, 8·4)
,, humid regions (decomposition slow)	1·0 ,, 10·0	1·7 ,, 7·0 (,, 4·2)

Westermann (302) has analysed humus from the Danish moors, and Gully (114) has studied humus from South Bavarian moors. Many of the older analyses have been collected by Wollny (319).

[2] This is shown by the analyses of Miklaus (*Zeit. f. Moorkultur u. Torfverwertung*, 1908, 285) and Mayer. Sostegni (268) in 1886 had shown that humus is readily fractionated,

in 1888 (19). Baumann's researches (9, 10) have carried the subject a good deal farther and it is now known that "humus" freshly precipitated by acids from an alkaline extract of soil, compost, etc., possesses the following colloidal properties:—

(1) Very high capacity for retaining water.

(2) Extraordinary shrinkage on drying.

(3) Reversibility, *i.e.* the freshly precipitated material redissolves when the precipitant is washed away.

(4) Is coagulated by acids and salts, the electric current and frost.

(5) Decomposes salts—calcium carbonate, calcium phosphate, etc.

(6) Forms difficultly soluble and easily decomposable colloidal mixtures with other colloids.

(7) Masks certain ion reactions (*e.g.* Fe cannot be detected by potassium ferricyanide, etc.).

(8) Forms absorption compounds.[1]

Schreiner and Shorey (250) have attempted a resolution of the "humic acid" and of the "crenic acid" (the part not precipitated by HCl) and have obtained the following substances from the alkaline extract:—

Substances precipitated by Acids (the so-called *Humic* and *Ulmic* Acids).	Substances not precipitated by Acids (the so-called *Crenic* and *Apocrenic* Acids).
Resin acids. *Resin esters.* *Glycerides.* *Paraffinic acid*, $C_{24}H_{48}O_2$, m.pt. 45°-48°, probably identical with the acid formed on treating paraffin with fuming nitric acid. *Lignoceric acid*, $C_{24}H_{48}O_2$, m.pt. 80°-81°, isomeric with above. *Agroceric acid*, $C_{21}H_{42}O_3$, m.pt. 72°-73°, a hydroxy fatty acid. *Agrosterol*, $C_{26}H_{44}O$, m.pt. 237°. *Phytosterol*, $C_{26}H_{44}O \cdot H_2O$, m.pt. 135°. Both of the cholesterol group.	*Dihydroxystearic acid*, $C_{18}H_{36}O_4$, m.pt. 98°-99°, identical with the acid formed on oxidising elaidic acid. *a-Picoline γ-carboxylic acid*, $C_7H_7O_2N_1$, m.pt. 239°, identical with the acid formed on heating uvitonic acid to 274°. *Xanthine*, $C_5H_4O_2N_4$. *Hypoxanthine*, $C_5H_4ON_4$. *Cytosine*, $C_4H_5ON_3 \cdot H_2O$. *Histidine*, $C_6H_9O_2N_3$. *Arginine*, $C_6H_{14}O_2N_4$. *A pentosan.*

Methods for estimating the amount of "humic acid" or "humates" in the soil have been devised and numerous analyses have been made, but no conclusions of any consequence have been drawn from the results. On the Rothamsted plots about one-half of the total nitrogen is contained in compounds soluble in alkalis, the proportion varying but little with the scheme of manuring. It has been maintained by Grandeau (111) and Hilgard (133) that these compounds are by far the

[1] The reddening of litmus paper is attributed to the absorption of alkali from the paper and consequently liberation of the red compound. But there is no reason why acids should not occur in the humus mixture.

most useful for making plant food, but there is no evidence in favour of this view.

No examinations have been made of the part of the organic matter insoluble in alkalis, but there is not the least reason for supposing that it is any less important than the soluble part.

Wax-like Constituents.

Some of the soil organic matter is wax-like in properties, interfering very much with the wetting of the soil and the movement of the water. As it only decomposes slowly it tends to accumulate in rich soils and to become rather troublesome. It can be extracted by organic solvents, *e.g.* toluene, and obtained as a yellowish-brown mass containing appreciable quantities of nitrogen (a soil yielded ·003 per cent. of a substance containing 3 per cent. of nitrogen in one of the writer's analyses).

The Nitrogen Compounds in the Soil.

It is convenient to collect together the main *data* connected with the nitrogen compounds of the soil. The total nitrogen in arable soils is usually about 0·15 per cent., in pasture soils about 0·3 per cent.; higher amounts are present in chalk soils and still higher in fen, moorland, and black prairie soils. About half of the nitrogen in arable soils is contained in compounds soluble in alkalis, and a small proportion in unstable compounds readily breaking down to ammonia. The amount of nitrogen present as free or combined ammonia is about ·0001 per cent. (*i.e.* 1 part per million) of arable soils not rich in organic matter, and some ten times this quantity in pasture or heavily dunged arable soils. There is considerable variation in the amount of nitrogen present as nitrate; rich garden soils may contain 60 or more parts per million (·006 per cent.), arable soils 2 to 20 parts (·0002 to ·002 per cent.), pasture soils rather less and woodland soils still less.[1] No soil constituent fluctuates more in amount than nitrates; plants and rain rapidly remove them and bacterial action rapidly forms them. The producing agencies are most active in spring, and work throughout summer and autumn, while the removal agencies are active in summer and winter. Thus the amount of nitrate actually present in arable soil is highest in spring, falls in summer, often rises somewhat in autumn, and falls again in winter as shown in Table XXXII. (p. 74).

[1] It is sometimes stated that woodland soils do not contain nitrates and are unsuited for nitrification, but Weis (301) has shown this to be incorrect.

TABLE XXXII.— NITRATES IN ARABLE SOILS (TOP 9") AT DIFFERENT SEASONS OF THE YEAR (RUSSELL).

	No Manure added. Poor Soil (·098 °/o N).	
	Cropped (Wheat).	Fallow.
1911.		
May 17	5·9	7·0
June 8	3·6	11·9
September 13	4·9	13·4
1912.		
February 15	3·5	5·0

	Manured Series, Barley Plots (Hoosfield).				
	Control (No Manure).	Ammonium Salts only.	Ammonium Salts and Super.	Ammonium Salts, Super, and Salts of K, Na and Mg.	Dung only.
1911.					
May 17	6·8	7·3	11·7	12·0	17·1
June 8	5·6	6·4	10·9	9·3	11·6
September 13	7·1	8·1	7·2	5·1	8·6
1912.					
February 15	3·7	3·3	4·7	3·7	7·7

Roughly speaking each 1000 parts of nitrogen in arable soils may be grouped as follows: soluble in alkali 500, unstable compounds 10, ammonia 1, nitrates 1 to 12.

The Constitution of the Soil.

The components of the soil do not form a mere casual mixture. A much more intimate mingling prevails, amounting almost to a loose state of combination, from which the separate substances are only extracted by drastic mechanical means, or gentle chemical treatment. The soil colloids and the calcium carbonate appear to be responsible for the formation of the compound particles, and as soon as they are altered by treatment first with acid and then with alkali the particles fall to pieces and the silt, clay, etc., can be readily separated by sedimentation processes. No method has been devised for measuring the size of the compound particles, but that they are large is shown by the following analyses of the same soil, one made after the usual treatment

with acid and alkali to break up the compound particles completely, the other made on the untreated soil, where the breaking up is only partial:—

	Disintegration complete.	Disintegration incomplete.
Fine gravel	·3	·2
Coarse sand	8·3	8·6
Fine sand	3·2	2·9
Silt	8·6	12·1
Fine silt	11·2	13·3
Clay	43·2	36·3

The existence of these compound particles puts out of the question any complete quantitative interpretation of a mechanical analysis. The properties of a soil are not the sum of the properties of the separate fractions—clay, fine silt, silt, etc.—because in a normal soil these fractions, which we may regard as the ultimate particles, are largely bound together into compound particles. How far the properties of the ultimate particles are modified by this union we cannot say, but no very profound alteration seems to take place in the sands and silts because the properties of the separate fractions, deduced by correlation methods from studies of numerous soils, agree tolerably well with the properties revealed by direct experiments on the fractions themselves. The finer particles are more changed, the result being to minimise the effects of their smallness. Thus, while the limits within which the properties of a soil fall are determined by the ultimate particles, a considerable variation is possible within these limits through the formation of compound particles.

It is unfortunate that so little is known about the compound particles, because they play a great part in determining the relationships between soil and plant growth. They can be disintegrated by various cultivation methods, such as ploughing the soil when wet, or by allowing the stock of organic matter and calcium carbonate to fall too low, and when this has happened the "clay" properties become emphasised, so that the soil loses its fine crumbly state and is very apt to become sticky when wet, and to dry into a hard cake through which young plants can only force their way with difficulty. The compound particles can be reformed by careful cultivation and by adequate additions of organic matter and calcium carbonate, but the process may take years, nor can it be hastened until it is better understood.

The reader cannot fail to have noticed how many of the important soil properties are due to colloids. The formation of these compound particles, the absorption of soluble manures, the retention of water

(in part), the swelling of the soil when wet and its shrinkage when dry, are all colloidal phenomena. If we regard the mineral particles as the skeleton of the soil we must look upon the colloids as clothing it in many of its essential attributes. How the colloids are arranged in the soil is not known, but the simplest view, and one in accordance with all the facts, is that the mineral particles, especially the fine silicate particles, are coated[1] with a colloidal complex containing silica, alumina, ferric oxide, alkaline bases and phosphoric acid derived from the weathering of the rock material and the so-called humus. These various components are not in true chemical combination, but in a state of absorption, or solid solution. The complex is decomposable by changes in temperature, concentration of the soil solution, etc., but it decomposes continuously and not in the *per saltem* manner of ordinary chemical reactions. It can interact with various solutions, absorbing certain substances as a whole—*e.g.* organic dye stuffs—or simply giving up to the solution an amount of base equivalent to what it has absorbed.

The study of the soil colloids is one of the most recent developments of the subject, and also one of the most promising.

A wholly different conception of the constitution of the soil has been put forward by Whitney and his colleagues of the Bureau of Soils, United States Department of Agriculture (303-6). Soil particles are supposed to arise by disintegration and to consist of the original minerals of which the rock was composed; little importance is attached to the weathered silicates that play so large a part in the view just set out. Colloidal properties and the special clay properties begin to appear when the disintegration has gone so far that the particles become very minute: these properties are not associated with any particular complex, but are supposed to be exhibited by any substance that is sufficiently finely divided. Most agricultural soils arise from the same minerals and are therefore of similar chemical constitution: in consequence the solution in contact with the particles, *i.e.* the soil moisture, is of similar composition and concentration for all soils. It is further supposed that the concentration of any particular ion in the soil solution is not altered by addition of soluble salts, any such addition only forcing out of the solution a number of the ions already there. Special importance is attached to this soil solution and it is regarded as the food of plants[2] and the source of fertility of the soil; indeed the function of the mineral part of the soil is mainly to hold up and distri-

[1] See also (88) and (89).

[2] It is interesting to note that a controversy on this point was going on fifty years ago when agricultural chemists first began to use water cultures. See Schumacher, *Landw. Versuchs.-Stat.*, 1863, v., 270-307.

bute this solution. But the view that it is unalterable in composition has led to some highly controversial deductions. In particular, soluble fertilisers like potassium salts are not supposed to increase the amount of food available to the plant, but to owe their beneficial effects to indirect actions in the soil, such as the precipitation of toxic substances, facilitation of movements of soil water, etc.

The fundamental differences between the two views are: (1) the nature of the colloidal substances of the soil; these are supposed by van Bemmelen and his school to be decomposition products of weathered silicates, and by Whitney to be particles of any composition provided the size is sufficiently small; (2) the constitution of the soil solution, van Bemmelen supposing it to be in equilibrium with a solid solution or colloidal complex, and therefore to depend as to its concentration on the masses of its constituents present in the complex, while Whitney supposes it to be in equilibrium with definite silicates and to be constant in concentration.

As the writer has shown elsewhere,[1] the evidence is rather against Whitney's view. The discussion that has gone on has, however, proved very fruitful in correcting the extreme chemical views once held and bringing out the fact first indicated by Schübler (253), but emphasised by Whitney, that the physical properties of the soil particles play a highly important part in determining fertility.

[1] *Science Progress*, July, 1911, p. 135.

CHAPTER IV.

THE CARBON AND NITROGEN CYCLES IN THE SOIL.

THE organic matter added to the soil by plants, etc., rapidly undergoes a number of changes in presence of air. Oxygen is slowly but continuously absorbed, and an almost equal volume of carbon dioxide is evolved, indicating that the main change is of the type—

$$C_n\ H_{2m}\ O_m + nO_2 = nCO_2 + mH_2O.$$

Thus the carbon in the soil tends to fall off relatively to the nitrogen, and the ratio $\frac{C}{N}$ which in the original plant material, *e.g.* the stubble, is about 40,[1] becomes reduced in the soil to 10 (Table XXXIII.). Other products are formed as well, including ammonia and the dark-coloured humus bodies already described, but the details of these changes are unknown. Investigations with the individual plant constituents, cellulose, fats, various organic acids, proteins have so far brought out little beyond the fact that they all oxidise to CO_2 in the soil, while the calcium salts of organic acids change to $CaCO_3$.

The rate of oxidation, as Wollny pointed out in 1884, (317), is very much diminished by traces of antiseptics, and the process is therefore apparently affected chiefly by micro-organisms. It shows a general increase up to a certain point with the amounts of moisture, organic matter and calcium carbonate present, although no sharp proportionality exists. It is closely related to productiveness; in a series of soils where the climatic and other external circumstances were similar the respective rates of oxidation were found to vary in the same way as the values for productiveness (Table XXXIII.).

The reasons for the connection between oxidation and fertility will become more evident as we proceed; the immediate connection is between oxidation and the activity of micro-organisms. In so far as oxidation is due to micro-organisms, its velocity obviously affords a measure of their activity. But there is a more fundamental relationship. Oxidation affords, so far as is known, the chief source of energy for the numerous micro-organisms of the soil. These organisms live in

[1] For leguminous crops, however, it is about 25.

TABLE XXXIII.—RATES OF OXIDATION, ORDER OF PRODUCTIVENESS, AND ANALYTICAL DATA FOR CERTAIN WOBURN SOILS. RUSSELL (238).

Name of Field.	Agricultural History.	Order of productiveness.	Oxygen absorbed in 17 days (mm.).	Analytical Data.			
				Nitrogen.	Carbon.	Loss on Ignition.	Calcium Carbonate.
Stiff Oxford clay	Wheat stubble	1	23·2	·252	2·53	8·73	·021
Road Piece	Wheat stubble preceded by mangolds fed on the land	2	18·7	·172	1·76	5·31	·072
Lansome field	Barley following mustard ploughed in; mineral manure . . .	3	14·1	·122	1·19	4·17	·027
Lansome field	Barley following tares ploughed in; mineral manure	4	10·2	·132	1·24	3·22	·051
Lansome field	Barley following tares ploughed in; no mineral manure . . .	5	8·2	·109	1·18	3·46	·008
Stackyard field	Wheat unmanured	6	8·2	·060	1·39	4·07	·004
Stackyard field	Wheat, ammonium salts only . .	7	7·8	·102	1·29	4·58	nil

darkness, and, therefore, unlike plants, derive no energy from light; indeed light is fatal to many of them. So much are they dependent on oxidation that in those soils where oxidation proceeds very slowly, as in certain moorland soils, there is a corresponding diminution in the micro-organic population.

The chemical investigations of the nitrogen cycle in soils have usually been confined to changes in the percentage of nitrogen and in the amount of nitrate present, and consequently they throw little light on the actual reactions taking place. Incomplete as they are, however, they have served a useful purpose by indicating the nature of the problem and furnishing material that has helped in unravelling the rather complex changes going on. Four cases have been studied.

1. The simplest is that of an ordinary arable loam kept moist, aerated, and at 10°-15° C.—these being normal conditions—free from vegetation and from the washing action of rain—these being abnormal conditions. A considerable formation of nitrate then takes place, about 3 per cent. per annum of the nitrogen being converted, and generally there is a small loss of nitrogen, presumably in the free state. How far the accumulation of nitrate would go under these circumstances has never been ascertained, because the experiment is necessarily very slow. Boussingault (49) stated that in eleven years one-third of the nitrogen of a rich soil changed to nitrate, and about one-half of the carbon to carbon dioxide.

2. If the conditions are made more normal by exposing the soil (still kept free from vegetation) out-of-doors to the action of rain and

weather generally, the nitrates do not accumulate but wash out, and can be detected in the drainage water. The soil thus loses nitrogen compounds, and in course of time the loss becomes very considerable. At Rothamsted a little plot of arable land $\frac{1}{1000}$ acre in extent has been kept free from vegetation by hoeing, but not otherwise disturbed, since 1870; it has now lost one-third of its original stock of nitrogen. The plot has been converted into a lysimeter by isolating it from the surrounding ground by cement partitions and then underdraining: the drainage water is collected daily and analysed. At the end of thirty-five years the amounts of nitrogen found as nitrate in the drainage waters were added up and found to be only 110 lb. less than the total loss of nitrogen from the soil. (Table XXXIV.).

TABLE XXXIV.—CHANGES IN NITROGEN CONTENT OF A SOIL KEPT FREE FROM VEGETATION FOR THIRTY-FIVE YEARS, BUT EXPOSED TO RAIN AND WEATHER. MILLER (200).

Per cent. of Nitrogen in Soil, top 9 inches.		*Lb. of Nitrogen per acre,* top 9 inches.			*Nitrogen recovered* as Nitrate, 1870-1905.
In 1870.	In 1905.	In 1870.	In 1905.	Loss in 35 years.	Lb. per acre.
·146	·102	3500	2450	1050	940

The obvious uncertainty attaching to so prolonged an experiment is reduced in this case by the fact that the determinations have for the last twenty years of the period been made by the same analyst. Miller found that the rate of loss of nitrogen (estimated by the quantities of nitrates in the drainage water) was about 40 lb. per annum in the earlier years, and fell below 30 lb. per annum in the later years. The experiment is not fine enough to justify any discussion of the missing 110 lb., but it shows that the loss of nitrogen is *mainly* due to leaching out of nitrates.

It is unfortunate that this highly important experiment has not been repeated with other types of soil, because there is evidence that a richer soil would lose *more* nitrogen than is accounted for by the nitrates formed, the rest presumably escaping as gas.

3. When the conditions are made wholly normal by allowing vegetation to grow, some of the nitrate is taken up by the plant and only a part is washed away, the division depending on the favourableness of the conditions for plant growth. The absorption of nitrate by the plant is much greater, and the amount of nitrate in the drainage water is therefore much less, on the Rothamsted wheat plots, where ample

supplies of potassium salts and phosphates are present than on the plots where these nutrients are less abundant and the crops smaller:—

Treatment.	Crop yield per acre per annum.		Nitrogen, recovered in Crop, lb. per annum.	Nitrogen present as Nitrate in Drainage Water during Autumn, parts per million.	Per cent. of N in Soil.	N lost from soil, lb. per annum.
	Grain, bushels.	Straw, cwts.				
Ammonium Salts containing 86 lb. N + No P or K salts	16·0	14·75	33·5	17·8	·106	67·5
Abundant supplies of P and K salts	26·7	30·75	45	8·5	·116	51

Part of the absorbed nitrate remains in the root and stubble, and is again added to the soil when the plant dies. Hence the percentage of nitrogen in the soil is higher where the conditions are favourable for the growth of plants than where, by the operating of some limiting factor, plants cannot make full growth and therefore leave untouched much of the nitrate to be washed away.

Most of the *data* hitherto accumulated are incomplete, because they refer only to crop results and take no account of nitrates washed out in the drainage water: fuller data cannot be obtained without costly and tedious lysimeter experiments. But in cases where the amount of drainage is known to be small the incomplete data are still of value for our purpose.

4. There is no reason to suppose that the amount of nitrogen in a prairie soil alters appreciably from year to year so long as the land is untouched. But directly ploughing and cultivation operations begin great losses of nitrogen set in, as shown by Shutt's analyses of the Indian Head soil, Saskatchewan (Table XXXV.). In this particular case there is practically no drainage water, and therefore little or no washing away of nitrates, yet only one-third of the lost nitrogen is recovered in the crop.

TABLE XXXV.—LOSSES OF NITROGEN CONSEQUENT ON BREAKING UP OF PRAIRIE LAND, TOP 8 INCHES. SHUTT (264).

	Per Cent.	Lb. per Acre.
Nitrogen present in unbroken prairie	·371	6940
,, ,, after 22 years' cultivation	·254	4750
Loss from soil		2190
Recovered in crop		700
Deficit, being dead loss		1490
Annual dead loss		68

The exhaustion of the soil is, therefore, not due to the removal of the crop, but to the cultivation.

Similar losses take place when heavy dressings of farmyard manure are repeatedly applied to land. One of the Broadbalk wheat plots receives annually 14 tons of farmyard manure per acre, containing 200 lb. of nitrogen. Only little drainage can be detected and there is no reason to suppose that any considerable leaching out of nitrates occurs, but the loss of nitrogen is enormous, amounting to nearly 70 per cent. of the added quantity. Alongside is a plot receiving no farmyard manure, from which in spite of drainage the loss is only very small.

TABLE XXXVI.—LOSSES OF NITROGEN FROM CULTIVATED SOILS, BROADBALK WHEAT FIELD, ROTHAMSTED, FORTY-SEVEN YEARS, 1865-1912.

	Rich Soil, Plot 2, lb. per Acre.	Poor Soil, Plot 3, lb. per Acre.
Nitrogen in soil in 1865	·175 % = 4,340	·105 % = 2,720
Nitrogen added in manure, rain (5 lb. per annum) and seed (2 lb. per annum)	9,730	330
Nitrogen expected in 1912	14,070	3,050
Nitrogen found in 1912	·245 % = 5,730	·103 % = 2,510
Loss from soil	8,340	540
Nitrogen accounted for in crops	2,550	750
Balance, being dead loss	5,790	− 210
Annual dead loss	123	− 5

Experiments of this kind have led to the conclusion that some gaseous product is formed in addition to nitrates, and, as no sufficient amount of ammonia can be detected, it is supposed that gaseous nitrogen is given off. The conditions for this decomposition appear to be copious aeration, such as is produced by cultivation, and the presence of large quantities of easily decomposable organic matter. Now these are precisely the conditions of intense farming in old countries and of pioneer farming in new lands, and the result is that the reserves of soil and manurial nitrogen are everywhere being depleted at an appalling rate. Fortunately there are recuperative actions, but one of the most pressing problems at the present time is to learn how to suppress this gaseous decomposition and to direct the process wholly into the nitrate channel.

We are now in a position to explain many of the anomalies and contradictions met with in investigations on the "availability" of organic manures. In these experiments it is usual to supply various nitrogenous

manures to a series of pots, or plots, and then measure the effect on the growth of the crop, and compare it with the effect of nitrate of soda, which is taken as 100. The idea is that the nitrogenous compound changes in the soil to nitrate, and this is taken up by the plant, which thereby becomes the agent for measuring the amount of nitrate formed. The method is simple, and gives the kind of information the practical man wants, but, unfortunately, it rarely gives the same results twice. *We can now see that it is incapable of accuracy*: in the first place the decomposition of the nitrogeneous compound does not merely give rise to nitrates but to gaseous nitrogen also, and the relative amounts of these two products vary with the conditions obtaining in the soil; in the second place the efficiency of the plant as a nitrate absorber is not constant, but depends on all the various factors influencing plant growth; finally, only in the rare cases where the experiment is conducted in a lysimeter is any allowance made for the unabsorbed nitrates. In spite of these drawbacks, however, availability measurements are of some practical value in classifying roughly the various manures and systems of cropping.

It is evident that there must be some recuperative agency, or the stock of soil nitrogen, which is never very great, would long ago have disappeared in old countries. Experiment has shown that soil *gains* nitrogen when it is allowed to remain undisturbed and covered with unharvested vegetation as in natural conditions. On the Broadbalk field a third plot adjacent to the two already mentioned was in 1882 allowed to go out of cultivation and has not been touched since; it soon covered itself with vegetation, the leaves and stems of which go to enrich the soil in organic matter. The gain in nitrogen is very marked, as shown in Table XXXVII. The gain is much influenced by the amount of calcium carbonate in the soil, and is considerably less on another plot in Geescroft field where only little calcium carbonate is present; whether this is due to any specific action, or to the changed physical conditions brought out by decalcifying a soil, is not clear. Gains of nitrogen also take place on land covered with perennial grasses and clovers even when the crop is mown or grazed. On wet clay pastures dressings of basic slag have been found to increase the nitrogen content of the soil, whilst potassium salts, such as kainit, have had the same effect on sandy soil.

In all these cases leguminous plants are present in greatest extent where the gains in nitrogen are greatest, but they are not necessarily the only nitrogen fixers.

Advantage is taken of this recuperative effect in all rotations by

TABLE XXXVII.—GAINS IN NITROGEN IN SOILS PERMANENTLY COVERED WITH VEGETATION—ROTHAMSTED SOILS LEFT TO RUN WILD FOR 22-24 YEARS. HALL (122).

	Broadbalk: $CaCO_3$, 3·32 per cent.				Geescroft: $CaCO_3$, 0·16 per cent.			
	Carbon, per cent.		Nitrogen, per cent.		Carbon, per cent.		Nitrogen, per cent.	
	1881.	1904.	1881.	1904.	1883.	1904.	1883.	1904.
1st 9 inches	1·14	1·23	·108	·145	1·11	1·49	·108	·131
2nd 9 inches	·62	·70	·070	·095	·60	·63	·074	·083
3rd 9 inches	·46	·55	·058	·084	·45	·44	·060	·065
Approximate gain in nitrogen, lb. per acre				2200				1400
Lb. per acre per annum				91·7				60

LAND LAID DOWN TO GRASS IN 1856 AND MOWN ANNUALLY (DR. GILBERT'S MEADOW, ROTHAMSTED).

	1856.	1879.	1888.	1912.
Per cent. of N in top 9 inches	[·152][1]	·205	·235	·338

alternating the periods of arable cultivation with periods of "*rest*" *in* grass and leguminous crops. In the old Norfolk rotations one year in four was given up to clover,[2] in modern rotations the clover or "seeds" mixture is left for two or three years before it is ploughed up, so that the enrichment may become more marked. Mr. Mason at Eynsham Hall[3] considerably enriched in nitrogen some poor Oxford clay by the growth of lucerne. But the gain in nitrogen does not go on indefinitely; in course of time a point of equilibrium is reached, higher or lower according to the soil conditions, where further gains are balanced by losses, so that the nitrogen content remains constant.

Thus there is an upper as well as a lower limit to the nitrogen content of the soil, the actual values depending on the soil conditions. Between these limits the nitrogen content may be maintained at any desired level, high when the ground is left in grass and leguminous crops, low when the ground is continuously cultivated. Unfortunately on our present knowledge it is impossible to maintain a high content of nitrogen on cultivated land except at a wasteful expenditure of nitrogenous manure.

Tentative determinations of some of these limits are:—

[1] Estimated.

[2] It was known to the Romans that vetches were a good preparation for wheat (*cf. Virgil*, Georgics, Book I., lines 73 *et seq.*).

[3] *Journ. Roy. Agric. Soc.*, 1904, lxv., 106-24.

	Black Organic Soils (containing more than 10 % of Organic Matter).	Chalk Soils.[1]	Loams.[1]	Sands.[1]
Upper limit	1	·42	·25	·20
Lower limit	·25	·13	·09	·03

The reactions involved in all these changes are obviously complex, but they have been partially disentangled, and we can now pass on to a more detailed consideration of the separate changes.

The Formation of Ammonia.

Ammonia is in all probability an intermediate product in the formation of nitrates. It is formed in the soil from the proteins of plant residues or manures, and the process is effected mainly by micro-organisms, but not entirely, for it still continues at a diminished rate in presence of antiseptics. The reaction has not yet been studied, but there is some evidence of the production of amino acids which subsequently hydrolyse, or oxidise. Although amino acids are in general fairly stable, several reactions are now known whereby they may be decomposed with production of ammonia:—

$$R{\cdot}CH{\cdot}NH_2{\cdot}COOH + O_2 = RCOOH + CO_2 + NH_3.$$ [2]

$$R{\cdot}CH{\cdot}NH_2{\cdot}COOH + H_2O = RCH{\cdot}OH{\cdot}COOH + NH_3.$$

$$R{\cdot}CH{\cdot}NH_2{\cdot}COOH + H_2O = RCH_2{\cdot}OH + CO_2 + NH_3.$$ [3]

It is not, however, known how they break down in the soil.

The investigations by Marchal (193) in 1893 of the method of ammonia production in the soil are so complete that little has since been added to the facts he ascertained. Müntz and Coudon (206, 207) had established the micro-organic nature of the process by showing that it was stopped by sterilisation. Marchal, therefore, made systematic bacteriological and mycological analyses of soils, and studied the action of the organisms thus obtained on solutions of albumin. Of the dozen or so varieties that invariably occurred, practically all decomposed the albumin and formed ammonia. *B. mycoides* proved very vigorous and was studied in some detail. The process was considered to be a simple oxidation necessary to the life of the organism; oxygen was absorbed and carbon dioxide evolved, the ratio $NH_3 : CO_2$

[1] Containing less than 10 per cent. of organic matter.
[2] Dakin, *Journ. Biolog. Chem.*, 1908, iv., 63.
[3] Ehrlich, *Zeitsch. Verein. Rübenzucker Ind.*, 1905, 539-67.

produced being 1 : 8·9. For complete oxidation of the carbon, hydrogen, and sulphur of the albumin molecule the ratio would be 1 : 10·3; but the change was known to be incomplete, and small quantities of leucine, tyrosine, and fatty acids could also be detected. Free oxygen, however, was not essential. When grown in a culture solution containing sugar and nitrate the organism took its oxygen from the nitrate, but it still produced ammonia.

Subsequent developments have been entirely on the bacteriological side. A number of organisms are now known to produce ammonia from complex nitrogen compounds, but soil bacteriologists have generally preferred to study the group as a whole, rather than isolate and study individual members. The application of this method of "physiological grouping" to soil problems is due to Remy (237). Soil is inoculated into a 1 per cent. peptone solution, and the ammonia produced after four days at 20° is taken as a measure of the "putrefactive power" or, as it is often called, the "ammonifying power" of the soil. Remy showed that certain soils known to give good crop returns for organic manures also possessed high putrefactive power, while Löhnis and Parr (186) have made the interesting observation that the putrefactive power of a soil falls off in winter, but rises in spring and continues at the higher level till late autumn. As a means of comparing soils the method gives better results if curves are plotted, showing the respective rates of ammonia production (Russell and Hutchinson (240)). But Stevens and Withers (271) have shown that it is very limited in its application, its chief use so far has been as an analytical test;[1] it has thrown little or no light on the processes going on in the soil. Indeed, so dependent is bacterial activity on temperature, concentration, reaction of medium (whether acid or alkaline), and other conditions that it may be doubted whether any method of study, except in the actual soil itself, will further our knowledge very much. Much better results are obtained by studying the rate at which nitrates form in the soil, this being, as we shall see later, the same as the rate of ammonia production. Soil bacteria can decompose other nitrogen compounds besides protein. Löhnis (187) has shown that they possess the remarkable power of decomposing calcium cyanamide Ca : NC : N to form NH_3 and $CaCO_3$, while other investigators have claimed that ferrocyanides, cyanides, and cyanates are also decomposed by soil bacteria.

[1] *E.g.* Lipman (176) has used it for testing nitrogenous organic manures.

Nitrification.

The ammonia formed by the action of soil bacteria, or added in manures, is changed to carbonate which is then rapidly converted by *Nitrosomonas* into nitrite, and this by *Nitrobacter* into nitrate, the changes proceeding so rapidly that only traces of ammonia or nitrite are ever found in normal arable soils (241). We may, therefore, infer that the production of nitrates is the quickest of the three reactions, the production of nitrites is slower, while the formation of ammonia is the slowest of all and sets a limit to the speed at which they can take place. Thus a measure of the speed at which nitrates are formed in soil does not measure the rate of nitrification, as is sometimes assumed, but the rate of ammonia production.

The essential facts of nitrification are readily demonstrated by putting a small quantity of soil—·2 to ·5 grams—into 50 c.c. of a dilute solution of ammonium sulphate containing nutrient inorganic salts and some calcium or magnesium carbonate, but no other carbon compound.[1] After three or four weeks at 25° the ammonia has all gone and its place is taken by nitrates. The conversion is almost quantitative, only an insignificant quantity of nitrogen being retained by the organisms.

The course of the oxidation is unknown, and nothing intermediate between ammonia and nitrous acid has been detected. Omelianski could obtain no evidence of an oxidase in *Nitrosomonas* (222). The action of both organisms seems to be entirely specific. Nitrosomonas oxidises ammonium carbonate and nothing else; it will not touch nitrates, urea, or the substituted ammonias. Even ammonium salts are only nitrified in presence of a carbonate that can change them into ammonium carbonate (296). Nitrobacter is equally specific, oxidising nitrites only and not ammonia.

Addition to the solution of almost any carbon compound other than calcium or magnesium carbonates retards the rate of nitrification, glucose and peptone being particularly harmful (312). Carbon dioxide suffices as the source of carbon for the growth of the organism. Godlewski showed that nitrification proceeds in solutions free from organic matter so long as the air supplied contained carbon dioxide, but stops as soon as the carbon dioxide is removed by passage over caustic potash. But the synthesis of complex cell substances from carbon

[1] Omelianski (221) used 2 grams each $(NH_4)_2SO_4$ and NaCl, 1 gram KH_2PO_4, ·5 $MgSO_4$, ·4 $FeSO_4$ in 1 litre of water, and added ·5 gram $MgCO_3$ for each 50 c.c. of solution used. Nitrite formation goes on in this solution. For nitrate production he used 1 gram each $NaNO_2$ and Na_2CO_3, ·5 each KH_2PO_4 and NaCl, ·4 $FeSO_4$ and ·3 $MgSO_4$ in 1 litre of water. Ashby (5) found that both processes went on simultaneously when he diluted the first of these solutions to one quarter the strength.

dioxide is an endothermic process requiring a supply of energy. In the case of the green plant, the only other living thing known to utilise carbon dioxide, the energy comes from light, the transformer being chlorophyll. Here, however, light is out of the question, and is even fatal to the organism. Winogradsky (311) suggested that the necessary energy is afforded by the oxidation of ammonia and of the nitrite, and he traced a definite relationship between the amount of ammonia oxidised and the carbon assimilated:—

	Experiment 1.	Experiment 2.	Experiment 3.	Experiment 4.
Ammonia oxidised (expressed as nitrogen)	722·0 mg.	506·1 mg.	928·3 mg.	815·4 mg.
Carbon assimilated	19·7 „	15·2 „	26·4 „	22·4 „
Ratio $\frac{N}{C}$	36·6	33·3	35·2	36·4

In these experiments mixed cultures were used, the nitrate producers predominating. More recently Coleman (71), using pure cultures of nitrate producers, obtained ratios varying from 40 to 44.

No useful hypothesis has yet been put forward to account for these remarkable facts. The whole subject deserves serious attention from some competent chemist.

It was somewhat hastily inferred that organic matter would have a retarding effect in the soil just as it has in culture solutions. From the outset, however, certain facts were known to be against this view: thus, there was a good deal of organic matter in the old nitre beds (235) and also in rich gardens, and yet nitrification went on vigorously in both cases. An exception was therefore made in favour of "humus" (208 and 209). Later on Adeney (1), and again Miss Chick (70), found another exception: the organic matter of the filter beds used in sewage purification. Coleman has now shown (71), and Stevens and Withers (272) have confirmed it, that *only in culture solutions* is organic matter injurious: in the soil it does no harm, and may even help the process. Thus quantities of dextrose that stopped nitrification entirely in Winogradsky and Omelianski's culture solutions were found to act beneficially in soil under normal conditions of temperature and moisture content. The discrepancy cannot yet be explained. Sucrose, lactose, and certain other non-nitrogenous compounds had no effect, but nitrogenous compounds were distinctly injurious.

The organisms will not tolerate an acid medium; a sufficient excess of calcium carbonate is therefore necessary both in culture solutions and in soils. Nor will they tolerate free ammonia. In culture solu-

tions the nitrate producer is somewhat sensitive even to ammonium salts, indeed both Warington (296) and Omelianski (p. 87) suppressed *it by maintaining* a *sufficient* concentration of ammonium sulphate; Löhnis has shown, however (185), that it is more tolerant in the soil. Some substance toxic to them is produced when soil is heated to 98° C. or more, and in such soils they cease to act. Neither nitrosomonas nor nitrobacter has been observed to form spores, or to survive temperatures above 45° C., or treatment with mild antiseptics like carbon disulphide and toluene. But so widely distributed are they and so readily can they spread in the soil, if the conditions are at all favourable, that they may reappear unless special precautions are taken to prevent infection. Thus, it is commonly stated that treatment of the soil with carbon disulphide merely depresses without killing the organisms. Russell and Hutchinson found, however, that the organisms did not reappear if the soil was kept carefully free from re-infection (240).

In pure cultures the organisms cannot tolerate absence of moisture, but die at once. In soil, however, they are more resistant. Absence of air puts an end to their activity.

There is some evidence that nitrobacter is more sensitive to adverse circumstances than nitrosomonas; it is also more rapid in action. Otherwise the two sets of organisms show very similar behaviour to external influences, their main difference being the fundamental one that nitrosomonas oxidises ammonia, but not nitrites, while nitrobacter oxidises nitrites, but not ammonia. There are also certain morphological differences. Nitrosomonas, or coccus, occurs in several forms, mostly oval in shape, ·5 to 1 μ wide and up to 2 μ long, but whether these are really distinct varieties is not known; a zooglea stage is also found; nitrobacter is rod-shaped, 1 μ long and about 0·3 μ thick, only one variety has been recognised. No other organisms are known with certainty to produce nitrates in the soil, nor can any other compound except ammonia be nitrified (220).

The Evolution of Gaseous Nitrogen.

A considerable loss of nitrogen occurs during the decay of plants, of dung and of soil organic matter in presence of air. The loss has been studied somewhat fully in the case of dung, because of its great technical importance, and it is attributed to an evolution of gaseous nitrogen during the processes of decay.[1] It only appears to go on so long as a supply of oxygen is available.

[1] See papers by Pfeiffer and others in *Landw. Versuchs-Stat.*, 1897, xlviii., 163-360, for an account of the loss from dung.

The oxidising bacteria are usually credited with the change, but no organism has yet been isolated capable of bringing it about. Nothing whatever is known about the mechanism of the process. No experiments appear to have been made with pure substances, or pure cultures of organisms, but only with the highly complex mixtures present in soil or dung. Further work is very desirable.

The Fixation of Nitrogen.

The first systematic search for a recuperative agency to make good the losses of nitrogen from the soil was started thirty years ago by Berthelot. He found that certain organic compounds could absorb free nitrogen under the influence of silent electric discharges, and at first attributed the natural recuperation to this cause. He also examined the possibility of bacterial action, as micro-organisms at that time were playing a large part in French science under Pasteur's influence. Accordingly he exposed sterilised and unsterilised sands and clays poor in nitrogen (·01 per cent. or less) to air in large closed flasks for five months, and found distinct gains in nitrogen in the unsterilised, but not in the sterilised soils. Fixation is, therefore, not due to any external physical cause which would operate equally in both cases, but to micro-organisms (26). This research was at once fruitful of results because it gave Hellriegel and Wilfarth the key to the clover problem (p. 16), and led Winogradsky (313) to search for the actual organism.

No investigator of our subject has shown greater ingenuity than Winogradsky in devising methods at once simple, direct and effective. In looking for the nitrogen-fixing organisms he inoculated soil into a medium containing every nutrient except nitrogen compounds: only bacteria capable of assimilating gaseous nitrogen could therefore develop, and these had a clear field. But he further recognised that the process was endothermic and required some source of energy, hence he added sugar to the solution. The method (known as the elective method) thus consists in making the conditions as favourable as possible for the group of organisms under investigation, and as unfavourable as possible for all others; it has proved extremely valuable in the subsequent development of soil bacteriology.

Winogradsky's solution contained 2 to 4 per cent. dextrose, a little freshly washed chalk, 0·1 per cent. K_2HPO_4, 0·05 of $MgSO_4$ and traces of NaCl, $FeSO_4$ and $MnSO_4$, together with a little soil. Under aerobic conditions nitrogen was assimilated and the sugar was decomposed with evolution of carbon dioxide and hydrogen and formation of

n-butyric and acetic acids in the proportion of three or four molecules of the former to one molecule of the latter, the two acids together accounting for nearly half the sugar. A little alcohol was found, but practically no non-volatile acid. There was a distinct relationship between the amount of nitrogen assimilation and the sugar decomposed, each milligram of nitrogen fixed requiring the oxidation of about 500 milligrams of sugar.

Three organisms were present, a clostridium and two bacteria, and they obstinately refused to be separated by the method of successive cultures. Not until recourse was had to anaerobic conditions were the two bacteria suppressed and the clostridium obtained pure. The bacteria having been isolated it appeared that the clostridium alone possessed the power of fixing nitrogen, but a fresh difficulty now arose because in pure cultures the organism would *only work under anaerobic conditions*. Only when the protective bacteria were simultaneously present did fixation go on in presence of air. The organism was called *Clostridium Pasteurianum*: it formed rods 1·2 μ thick and 1·5 to 2 μ long, and also spores (314).

In order to simplify the bacterial flora Winogradsky had heated his soil to 75°, thereby killing non-spore formers, but later on Beijerinck (14 and 15) working with unheated soil, discovered three other nitrogen-fixing organisms: Azotobacter chroococcum (so called because, as it ages, it turns brown and finally almost black), Granulobacter and Radiobacter.[1] Of these azotobacter is the most active; it forms large cocci, or rods, 4 to 6 μ in thickness, and does not produce spores. It differs in two important respects from clostridium: (1) it is aerobic; (2) it produces practically no butyric acid. Its effects can be studied by inoculating 0·1 to 0·2 grams of soil into 100 cc. of tap water containing 2 per cent. mannitol, ·02 per cent. K_2PO_4, and sufficient $CaCO_3$ and keeping for some weeks at 27° to 30° C. in a thin, well-aerated layer[2] in an Erlenmeyer flask. Azotobacter fixed more nitrogen than clostridium per gram of sugar decomposed; Gerlach and Vogel's (104) results are:—

Glucose decomposed, mgs.	1,000	2,000	3,000	4,000	5,000	6,000	7,000	10,000	12,000	15,000[3]
Nitrogen fixed, mgs.	7·4	13·5	17·8	31·4	39·4	45·9	59·9	91·4	127·9	62·9
Nitrogen fixed, per gram of sugar	7·4	6·8	5·8	7·8	7·9	7·6	8·5	9·1	10·7	—

Mean 8·9 mgs. nitrogen fixed for 1 gm. sugar.

[1] Since shown by Stoklasa (276) to possess only slight nitrogen-fixing power.

[2] Later on Beijerinck used calcium malate in place of sugar, and showed also how to make plate cultures of the organisms (16).

[3] The sugar was not *all* used up in this experiment.

The nature of the compound is also important. Löhnis and Pillai (188) found that the following amounts of nitrogen were fixed per gram of compound decomposed :—

Mg. of Nitrogen Fixed.	
7·5 to 10	Mannitol, xylose, lactose, lævulose, inulin, galactose, maltose, dextrin, sucrose + calcium carbonate.
5 to 7·5	Sucrose alone, dextrose, sodium tartrate + calcium carbonate, glycerol + calcium carbonate.
2·5 to 5	Starch, sodium tartrate, sodium succinate, calcium lactate.
1 to 2·5	Sodium propionate, sodium citrate, glycerol alone.
Nil	Calcium butyrate, potassium oxalate.

Little is known of the chemistry of the change, even the fate of the sugar has not been definitely ascertained. The only obvious product is carbon dioxide, fatty acids being formed only in small quantities, in sharp contrast with clostridium.

Starting with 15·9 grams of dextrose Stoklasa (276) recovered 7·9 as carbon dioxide, 0·3 as ethyl alcohol, 0·2 as formic acid, 0·7 as acetic acid, 0·2 as lactic acid, but could not trace the remaining 6·5 grams.

The nitrogen is found partly in compounds dissolved in the liquid, but mostly in the bacterial mass. The organism is remarkably active, one gram weight evolving no less than 1·3 grams of CO_2 in twenty-four hours (273). An adequate supply of phosphate, calcium carbonate and other mineral nutrients is essential, any deficiency limiting the amount of fixation. Traces of nitrogen compounds are helpful in the early stages, but larger quantities reduce the amount of fixation, and may themselves suffer some change: thus sodium nitrate is partially reduced to nitrite and ammonia. Several forms of azotobacter are now known: *A. agilis*, *A. vinelandii*, etc., and also various less efficient nitrogen fixers that more resemble clostridium, such as amylobacter (53) and granulobacter, some of which are aerobic and others anaerobic, but all form spores.[1] The great distinction between the two groups is that the azotobacter give carbon dioxide as the chief product from the sugar, while the others, even the aerobic organisms, form butyric acid in considerable amount and fix smaller quantities of nitrogen. Amylobacter also makes and stores glycogen, a property possessed by few other micro-organisms.

Kossowitsch (154) has shown that a mixture of azotobacter and algæ, especially nostoc, can work together very well, the algæ furnishing the necessary carbon compounds, while the azotobacter fixes

[1] A list is given by C. B. Lipman in *Journ. Biol. Chem.*, 1911, x., 169-82.

nitrogen, an observation that has been confirmed by Bouillac (43 and 44). Sand has been found to gain nitrogen where the growth of algæ was possible and the proper bacteria were present.[1]

How far azotobacter is active in the soil in natural conditions has not been definitely ascertained, partly because of the analytical difficulties of measuring small gains of nitrogen, and partly because of the losses of nitrogen that, as we have seen, go on in presence of organic matter. The mere occurrence of azotobacter in the soil is no proof that it is actually fixing nitrogen, the only satisfactory evidence would be a demonstrated gain in nitrogen effected by azotobacter, all other possibilities being ruled out by the experimental conditions. The usual method of investigation has been to add sugar, or other carbohydrates, to the soil and measure the change in nitrogen content after various intervals of time. Generally, there is a gain of nitrogen; losses are, however, often recorded (248, 151, etc.), whilst a certain loss of nitrate invariably sets in (p. 99). A. Koch (151) added successive small doses of dextrose to 500 grams of loam, mixed with sand and spread on plates to secure copious aeration, kept uniformly moist and at 20° C. Nitrogen fixation began very soon and reached its maximum after eighteen weeks, when losses set in; the results are given in Table XXXVIII.

TABLE XXXVIII.—NITROGEN FIXED IN SOIL BY BACTERIAL ACTION IN PRESENCE OF DEXTROSE. KOCH (151).

Increments of Dextrose per 100 grams of Soil.	Total Dextrose supplied in grams, per 100 grams. of Soil after				Mgs. N. Fixed per 100 grams. of Soil after			
	5 weeks.	8 weeks.	18 weeks.	26 weeks.	5 weeks.	8 weeks.	18 weeks.	26 weeks.
	June 26.	July 20.	Oct. 3.	Nov. 30.	June 26.	July 30.	Oct. 3.	Nov. 30.
·2	1·0	1·6	3·6	5·2	8·3	14·9	17·8	18·9
·5	2·5	4·0	9·0	13·0	20·1	32·5	36·8	31·6
1·0	5·0	8·0	18·0	26·0	35·8	57·2	58·7	52·7
1·5	7·5	12·0	27·0	37·5	40·5	66·7	68·5	66·8
2·0	8·0	14·0	26·0	36·0	43·9	78·8	80·0	78·8

For each gram of dextrose supplied in the small doses about 8 milligrams of nitrogen were fixed during the first eight weeks; but only 4 or 5 milligrams later on. In larger doses the sugar was less effective, only 5 to 6 milligrams of nitrogen being fixed per gram of sugar at first and 3 milligrams later.

Pot experiments showed that the nitrogen thus added to the soil became available for plant food. Dextrose and sucrose first depressed

[1] A. Koch has collected instances in *Lafar, Tech. Mykologie*, Bd. iii., p. 15.

the crop, then caused an increase, and finally left the soil richer in nitrogen at the end of the experiment than at the beginning (Table XXXIX.).

TABLE XXXIX.—EFFECT OF DEXTROSE AND SUCROSE ON THE PRODUCTIVENESS AND NITROGEN CONTENT OF THE SOIL. KOCH (151).

Sugar added per 100 grams. of Soil.	Crops Obtained.				Total N. removed in Crop.	Nitrogen left in Soil, Spring, 1906.	
	Oats, 1905.		Sugar Beets, 1906.				
	Dry Matter.	Yield of N.	Dry Matter.	Yield of N.	Grams.	Total N. per cent.	N. as Nitrates, parts per million.
	100	100	100	100	0·5914	·093	10
2 °/₀ dextrose	32·8	62·5	1·86	190	0·6814	·105	17
2 °/₀ cane sugar	33·3	58·7	179	195	0·680	·105	15
4 °/₀ " "	37·7	78·1	283	339	1·0092	·119	37

But if the soil temperature fell too low nitrogen fixation ceased: it was not observed at 7° C. although it appeared to go on at 15° C. The optimum temperature lies between 25° and 30° C.

Increased yields of sugar-cane have followed the application of molasses to soils at the Station Agronomique and on Mr. Ebbel's estate[1] in Mauritius, where the residual effect is well shown, and also in Antigua (192). Peck in Hawaii, on the other hand, observed marked losses of nitrate.

An increase in crop following the application of sugar, or starch, to the soil is not evidence of nitrogen fixation, but might equally well be adduced to show that sugar and its decomposition products are direct plant nutrients. Only when an actual gain in nitrogen is demonstrated by analysis does the proof become satisfactory. As a practicable scheme the addition of sugar to the soil would be out of the question for field work. Pringsheim (231) has shown, however, that certain decomposition products of cellulose also serve as sources of energy to clostridium and presumably also to azotobacter. These particular products (which were not identified) are apparently not always formed in the soil (152), but are readily produced in culture solutions under the action of the mixed bacterial flora from soils, composts, dung and river mud. The difficulty of material might therefore be overcome because large quantities of cellulose are available on the farm in the form of straw. But there still remains the question of temperature. Azotobacter, as we have seen, requires more warmth than many other organisms, and according

[1] See *The Agricultural News*, 1908, vii., 227; 1910, ix., 339, and 1911, x., 179.

to Koch's experiments ceases to work at 7° C. Thiele read temperatures daily for three years of arable and grass soils at different depths at Breslau (282), and concluded that only rarely were they favourable for azotobacter. But it is impossible to argue from a culture solution to the soil, and indeed Lohnis has shown that the mixed cultures of the soil are almost as effective at 10° as at 20°:—[1]

10°-12° C.	20°-22° C.	30°-32 C.
3·15 mg.	4·55 mg.	4·27 mg. nitrogen fixed.

It seems legitimate to conclude that azotobacter fixes nitrogen in well-aerated soils sufficiently provided with calcium carbonate, potassium salts and phosphates, carbonaceous material of the right kind and moisture, so long as the temperature is high enough. Where the air supply is diminished owing to the close texture of the soil there is still the possibility of fixation by clostridium. Ashby (7) found that the relative distribution of azotobacter and clostridium at Rothamsted depended on the amount of calcium carbonate in the soil; wherever any notable quantity was present, azotobacter invariably occurred: otherwise clostridium alone was found. It is not certain whether this result is due to some specific action of calcium carbonate or to the shortage of air supply consequent on the bad mechanical state always induced at Rothamsted when calcium carbonate is absent.

Nitrogen Fixation by Bacteria in Symbiosis with Leguminosæ.

After Hellriegel and Wilfarth's great discovery of the relationship between bacteria and leguminosæ (p. 16) many unsuccessful attempts were made to isolate and study the organisms by the methods then in vogue. In 1888 Beijerinck (11) broke away from the ordinary meat-bouillon-gelatin plate and substituted a slightly acid medium made up of infusion of pea leaves, gelatin (7 per cent.), asparagine (·25 per cent.) and sucrose (·5 per cent.). Growth readily took place and the colonies yielded rods 1 μ wide and 4 to 5 μ long, some of which showed signs of bacteroid formation, and "swarmers" 0·9 μ long and 0·18 μ wide, these being among the smallest organisms known.[2]

None of these organisms, however, could be found in the soil, nor indeed has any one yet succeeded in finding them there although their existence cannot be doubted. Their mode of entry into the pea was studied by Prázmowski (228), and later by Nobbe and Hiltner (216). The root hair is attacked, presumably by the "swarmer," and a filament,

[1] *Mitt. Landw. Inst., Leipsic*, 1905, vii., 94.

[2] Golding has shown that they will even pass through a porcelain filter and has prepared pure cultures in this way.

known as the infection thread and shown to be formed of rapidly multiplying bacteria, gradually extends up into the root where the nodule begins to form; beyond this, the organisms do not penetrate. The morphological changes have been described by Marshall Ward (293), Miss Dawson (80, 81) and others. Soon the organisms surround themselves with slime and appear as bacterial rods, which then change to the characteristic branched or Y-shaped bacteroids and assimilate free nitrogen. The organisms have a remarkable power of discrimination and only enter in any quantity the particular species of plant to which they are accustomed; they can, however, train on to other species, but they then lose the power of attacking their original hosts.

Hiltner (134 and 135) regards them as parasites attracted chemotactically to the root hair by root excretion, but prevented from getting too far into the plant by excess of the attracting material, which now becomes a deterrent. He grades them according to their virulence, the less virulent either being unable to enter the plant, or, if they do enter, being quickly resorbed, or only fixing little nitrogen; the more virulent on the other hand bring about energetic fixation. As evidence he adduces the well-known fact that infection proceeds best in plants weakened by nitrogen starvation, and scarcely takes place at all in plants growing vigorously on rich soils. The parasitism is beneficial to both parties: the plant gains nitrogen and the organism gains carbohydrates.

In its general outlines the process has been reproduced artificially. Leguminous plants can be fed with nitrogen compounds and made to grow perfectly without the organism. On the other hand, the organism can be grown on artificial media containing carbohydrates,[1] made to pass through all its stages from swarmers to bacteroids, and to fix nitrogen.[2] The change to bacteroids is conditioned by the presence of carbohydrates or of small quantities of various acids, such as are known to occur in the plant (277). The fixation of nitrogen rapidly comes to a stop unless the resulting compound is removed, as in the plant. Golding has attained this end by an ingenious filtering device, and has thus succeeded in fixing considerable quantities of nitrogen. He has also shown that the reaction of the medium during actual fixation is alkaline, but changes to acid when fixation is stopped by the accumulation of nitrogen compounds. An actual loss then seems to set in (108, 109).

The chemistry of the process is unknown; even the changes in the carbohydrates of the culture medium have not been worked out. Nitro-

[1] Harrison and Barlow (126) used maltose: other observers have used an infusion of the host plant. Neumann suggests pentosans (213).

[2] See also (13).

gen fixation is known to take place in the nodule, which thus becomes richer in nitrogen than the rest of the root,[1] and its final product is supposed to be a soluble protein which is passed on to the plant.

But the amount of nitrogen fixed in this way is so large that it is easily measured on the field. When the host plant dies, or is ploughed into the ground, the nitrogen compounds speedily change into plant food. A uniform piece of ground at Rothamsted was divided into two parts: on one a crop of clover was taken, on the other barley was grown. After the crops were removed samples of soil were taken for analysis, and then barley was grown on both plots. The analytical results were :—

	Plot where Clover was Grown.	Plot where no Clover was Grown.
Nitrogen in crop (1873) lb. per acre	151·3 (in clover)	37·3 (in barley)
Nitrogen left in soil after crop was removed (1873) per cent.	·1566	·1416
Nitrogen in crop (1874) lb. per acre	69·4 (in barley)	39·1 (in barley)

These facts are well known to the practical man, and are utilised for increasing the nitrogen supply of cultivated soils and for reclaiming barren sands and clays (pp. 84 and 126). Leguminosæ are among our commonest plants, both wild and cultivated. Wherever they grow they lead to enrichment of the soil in organic nitrogen compounds through the operation of the nodule organisms. The difference between the action of this organism and that of azotobacter is that it gets its carbohydrates from the plant, and is, therefore, independent of soil organic matter. Thus, it operates perfectly well in the poorest soils provided potassium salts, phosphates and calcium carbonate are present in sufficient quantity for the host plant, while azotobacter (except where it is associated with algæ, a case that requires further investigation) requires a supply of organic matter in the soil, and therefore only works in fairly rich soils where its effects are more difficult to measure.

[1] Stoklasa's analytical results with yellow lupines (*Landw. Jahrb.*, 1895, xxiv., 827, are :—

	Blossom Formed.	Seed beginning to Form.	Seed Ripe.
Nitrogen in nodule, per cent.	5·2	2·6	1·7
Nitrogen in rest of root, per cent.	1·6	1·8	1·4

Few improvements in agriculture have produced more marked effects than the extension of leguminous cropping. Where a new leguminous crop is being grown for the first time it may be necessary to introduce the appropriate organism, as has been successfully done in Canada by Harrison and Barlow (126), and on the North German moors by Hiltner (135; see also 217 and 218). But, in general, these inoculations have not proved useful, and they have never come into farming practice: the high hopes sometimes entertained that the whole problem of nitrogenous manuring—the most costly item in the farmer's fertiliser bill—might reduce itself solely to bacterial inoculation have never been realised. The problem is extraordinarily fascinating and never fails to arouse immense popular interest, but it is elusive and treacherous, and has raised more false hopes and led to more disappointments than any other in our subject.

Denitrification.

If the air supply of the soil is cut off by water logging, or in the laboratory by means of an air pump, the nitrates rapidly disappear, whilst nitrites, ammonia, or gaseous nitrogen are formed. The conditions can be so arranged that the decomposition of nitrate-bouillon by soil shall give rise to notable quantities of gaseous nitrogen, nitrous oxide (18 and 279), or nitric oxide (168).

This decomposition of nitrates has long been known. The reduction to nitrite was shown by Meusel in 1875 (198) to be bacterial, since it could be stopped by antiseptics. The property appears to be generally possessed by bacteria and was shown by no fewer than 85 out of 109 kinds investigated by Maassen (190).

The formation of gaseous products is effected by a smaller but still considerable number of organisms; these were first investigated by Gayon and Dupetit (101-103), and by Déhérain and Maquenne (82).

The physiological significance of the reduction appears to be that nitrates can supply oxygen to the organisms when free oxygen is no longer obtainable. It is not simply a reaction between the organism and the nitrate: easily oxidisable organic matter must be present at the same time. The partially decomposed organic matter of the soil —the "humus"—does not seem to be very serviceable (274).

There is a very sharp contrast between the bacterial production and the bacterial destruction of nitrates. Nitrate production is the work of one organism only at each stage, and the end result is a single product quantitatively equivalent to the original ammonia; no single chemical process oxidises ammonia in this complete manner. The

bacterial reduction of nitrates, on the other hand, gives no single product, but a number of products not in any simple ratio, whilst the chemical reduction can readily be made to go quantitatively to ammonia.

Whether denitrification goes on to any extent in properly drained soils is doubtful, because the three essential conditions, lack of air, presence of much easily decomposable organic matter and of nitrate are rarely attained. In 1895 Wagner and Maercker startled the agricultural world by announcing that unrotted dung destroys the nitrates in the soil and reduces the crop yield (291). Their experiments were criticised by Warington (297) who pointed out that their dressings of dung were enormous and their results would not apply to ordinary farm practice. But it goes on to a marked extent in wet soils. Nagaoka (211, see also 74) has shown that nitrate of soda frequently depresses, instead of increasing, the yield of rice, sagittaria and juncus on the swamp soils of Japan, an action which he attributes to the formation of poisonous nitrites. Organic manures are always used on such soils.

Assimilation of Ammonia and Nitrates by Bacteria and other Micro-organisms.

Various bacteria and moulds capable under suitable conditions of assimilating ammonia have been isolated from soils. They are not active in ordinary arable soils rather poor in organic matter; Schlösing *père* (245) recovered as nitrate 98 per cent. of the added ammonium compounds, so also did Russell and Hutchinson. In peaty soils, however, the assimilation of added ammonia appears to be more pronounced, amounting to nearly 30 per cent. in Lemmermann's experiments (170).

Certain organisms are capable of taking up nitrates. Whether the action goes on in the soil is not clear, but it is not excluded by the conditions; it requires easily decomposed organic matter (38) and air, in which respect it differs markedly from denitrification proper; it apparently goes on when sugar is added to the soil (152). But such assimilation does not necessarily involve any loss of nitrogen, for as the bacteria die they are probably decomposed with formation of ammonia and nitrates once again.

Summary of the Changes Taking Place and the Agencies Involved.

It is unfortunate that no synthesis of a soil has yet been effected, and consequently the preceding analysis of the changes taking place cannot be tested by reconstructing the whole process out of its constituent parts. On the whole the evidence is satisfactory as to the general course of the changes, but insufficient for sorting them out quantitatively and precisely. The following scheme summarises them as completely as is possible at present:—[1]

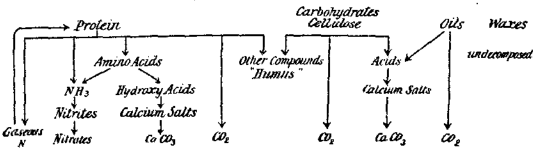

Fig. 6.

There is good reason to suppose that all of these changes are effected by bacteria, but the evidence is by no means conclusive. The obvious test of working with sterilised soil is out of the question, because soil can only be sterilised by drastic methods that wholly change its character. The fact that antiseptics put an end to most of the reactions always used to be regarded as sufficient proof of their bacterial nature, but this argument has lost much of its force since Bredig and others[2] have shown that indisputably dead materials like spongy platinum partially lose their power of bringing about chemical changes when treated with antiseptics. Now the soil is a spongy mass, measurably radio-active,[3] containing numerous colloidal bodies not much investigated, but conceivably capable of acting as catalysts, and it is possible to imagine a series of catalysts that would bring about all the known changes and be put out of action by antiseptics. Hypotheses of this nature have indeed been put forward from time to time: some ammonia is known to be produced by chemical processes in the soil, Sestini (263) has supposed that it is oxidised catalytically by the ferric oxide always present to nitrites and nitrates, while Loew (184) states that nitrogen can be catalytically "fixed" and converted into nitrates. Russell and Smith (242) failed to reproduce these changes catalytically. Indeed the

[1] It will be noticed that these processes show certain resemblances to those of sewage purification beds, as worked out by Adeney (1) and Fowler (98). For the decomposition of fats, see Rahn (232).

[2] *Cf.* Bredig and Ikeda, *Zeit Physikal Chem.*, 1901, xxxvii., 1-68.

[3] See *e.g.* Joly and Smyth, *Sci. Proc. Roy. Dublin Soc.*, 1911, xiii., 148-61.

chief argument in favour of the bacterial hypothesis is that all known soil processes can be reproduced in the laboratory by soil bacteria acting under conditions comparable with those known to obtain in nature, whilst they have not been produced by catalysts. The bacterial hypothesis, therefore, remains the simplest and most satisfying, but there is room for more evidence before it can be regarded as positively established.

It is certain that living bacteria occur in the soil in addition to those present as spores. Some idea of the relative proportions of these two forms was obtained by making gelatin plate cultures of soil before and after treatment with toluene, which destroys living forms but not spores, or at any rate not all spores (Table XL.). Spores only form about 25 to 30 per cent. of the total numbers, and for some unknown reason do not accumulate. The bacterial numbers are seen to be very high, but even these figures do not represent the true totals, and no medium has yet been devised that allows of the growth of all the organisms known to occur in the soil.

TABLE XL.—NUMBERS OF ACTIVE BACTERIA AND SPORES OCCURRING IN SOILS AND CAPABLE OF GROWTH ON GELATIN PLATES. (RUSSELL AND HUTCHINSON (240).) MILLIONS PER GRAM OF DRY SOIL.

	Arable Soil.	Rich Greenhouse Soils.
Forms killed by toluene (*i.e.*, active forms) .	7·4	39·6
Spores surviving toluene	2·9	13·3
Total growing on gelatin . . .	10·3	52·9

The active forms must be held responsible for some at least of the oxygen absorption, carbon dioxide evolution and decomposition going on. Under comparable soil conditions a distinct relationship exists between the productiveness of the soil and the amount of bacterial activity, although it cannot be expressed in any definite form. Counts of the numbers of bacteria by any particular method fail to give results sharply connected with productiveness (although there is a general relationship) because the organisms are of the most varied description (110), and of widely different efficiency as food makers. Nor, on the other hand, have the methods of physiological grouping helped much, since they necessitate growth in culture media wholly different from the soil under temperature and water conditions that never obtain in nature. Not until the fundamental difficulty has been overcome of synthesising a soil identical with natural soil will it be possible fully to interpret the many interesting observations that soil bacteriologists are now accumulating.

CHAPTER V.

THE BIOLOGICAL CONDITIONS IN THE SOIL.

IT is now necessary to study the soil conditions that determine the growth not only of plants but also of the micro-organisms that, as we have seen, make new plant food out of old plant residues, and render possible the continuation of vegetable life on the earth. These conditions are water supply, air supply, temperature, food supply, and absence of injurious factors.

The Water-Supply of the Soil.

The rain-water falling on the soil immediately begins to soak in, but during its passage a certain amount is retained on the surface of the particles and never drains away; it forms a series of continuous films exhibiting, as Briggs (55) has shown, all the special properties associated with the surfaces of liquids. Thus, the water remains on the particles against the force of gravity. Further, it tends to distribute itself evenly throughout a uniform mass of soil by moving from places where the curvature of the films is flat to places where the curvature is sharp. How far this tendency is an important factor in the distribution of water in the soil is not known; Leather's results at Pusa (167) indicate that it may not be very marked. There are at least three factors that complicate the problem:—

1. Evaporation is continually reducing the thickness of the films, and finally breaks them altogether, so that the soil becomes dry. It then remains dry till more rain falls, because the waxy material on the particles, like grease on a surface of glass, prevents the spread of the films, and may even make wetting by the rain a matter of some difficulty.

2. The pores of the soil are so small that there is considerable friction, retarding very much the speed of the water movements. In clay soils this retardation is particularly marked, and not uncommonly causes soils to crack with drought even within two or three feet of a stream. Not only are the film movements affected but the downward percolation also, so that free water is retained near the surface for a

considerable time, often over the interval between one shower and another. In sandy soils the pores are larger and the water movements more rapid.

3. The soil colloids absorb water without, however, holding it very strongly. It loses all power of movement and no longer forms an actual free film, but it still appears to be available for the use of micro-organisms and plant roots.

These facts explain the law empirically set out many years ago by Schübler (253) that the moisture content of a soil is a function of its structure. A sandy soil soon becomes wet, but dries again rapidly. Its large pores allow rapid percolation of the free water; its relatively small total surface (a consequence of the large size of its particles) holds a proportionately small amount of water; it possesses but little colloidal material to absorb and retain water. Addition of easily decomposable organic matter increases the amount of colloid and thus increases the water-holding capacity; addition of clay increases the colloids and the total surface, and also partially blocks up the pores, the two last effects being due to the smallness of the clay particles. Under equal conditions of water supply, clay soils and soils rich in organic matter are, therefore, much moister than sandy soils: illustrations are given in the Table on p. 67 and in Table XLII.

TABLE XLII.—MOISTURE CONTENT OF SANDY, LOAMY, AND CLAY SOILS AT WOBURN LYING NOT FAR APART AND UNDER APPROXIMATELY EQUAL RAINFALL CONDITIONS. RUSSELL.[1]

	Sandy Soil (Clay = 5·0 per cent.).	Loamy Soil (Clay = 9·3 per cent.).	Clay Soil (Clay = 43·0 per cent.).
Highest observed	14·0	16·5	35·0
Lowest observed	1·1	6·0	15·8
Mean of all observations	9	12	27

We can gain a better idea of the meaning of these results by translating them into volumes. The soil is a porous mass, and a large part of it is not occupied by solid matter at all but by air and water. Comparison of the true specific gravity determined by the specific gravity bottle with the apparent density obtained by weighing a block of soil of which the *in situ* volume is known, shows that the solid matter forms 50 to 65 per cent., leaving 50 to 35 per cent. of pore space. Organic matter increases the pore space in consequence of its "lightening" action (p. 66).

[1] The determination is made by drying at 40° C.

TABLE XLIII.—PORE SPACE, WATER CONTENT, AND AIR CONTENT OF CERTAIN SOILS. RUSSELL.

Soil.	Specific Gravity of Dry Soil.		Volume occupied in Natural State by		Volume of Water.		Volume of Air.	
	Apparent.	True.	Solid Matter.	Air and Water (Pore space).	In Normal Moist State.	After Period of Drought.[1]	In Normal Moist State.	After Period of Drought.
Poor heavy loam (Rothamsted) (Loss on ignition, 4·3 %)	1·57	2·36	65·9	34·1	23·2	17	10·9	17·1
Heavily dunged arable soil (Rothamsted) (Loss on ignition, 10·0 %)	1·46	2·31	61·8	38·2	30·3	20	7·9	18·2
Pasture soil (Loss on ignition, 13·0 %)	1·17	2·22	52·7	47·3	40·0	22·3	7·3	25

The actual quantity of water present in the soil is constantly changing from the saturation quantity, which completely fills the pore spaces, to the minimum amounts recorded in Table XLIII., but the extreme values only persist for a very short time in normal soils, the usual fluctuations being between much narrower limits. Thus, a considerable bulk of the soil is really water spread as films over the particles or held up in the pore spaces, but unfortunately the actual thickness of the films cannot be calculated from the available data.

The whole of this water is not generally available for any one plant. *Water must be supplied to the plant at least as quickly as it is lost by transpiration, otherwise wilting sets in. Now the rate of supply of soil* water is simply the speed at which water can move in the soil, and this, as we have seen, depends on the amounts of clay and colloidal matter present; it may easily fall below what is wanted for maintaining equilibrium in the plants growing on soils rich in clay or organic matter. Another factor also comes into play. The soil water is not pure, but contains dissolved substances which do not necessarily enter the plant simultaneously with it. As removal of the water goes on the solution becomes more concentrated, and may finally reach a point where it is *too concentrated to enter the plant.* Thus, *wilting will often set in on* clay or humus soils containing several per cents. of water.

Determinations have been made by Heinrich (127), Briggs (56) and Crump (73) of the water still *remaining in the soil when wilting begins,* and it is customary to speak of this as "unavailable" water. The ex-

[1] Driest periods of 1909 and 1910. During the abnormal drought of 1911 the numbers fell to 6 and 8 for the first two soils.

pression is unfortunate, because it entirely disregards the water that would be utilised if only it could travel quickly enough to the root, and assumes that the whole of the untouched water is present in some state other than the free state. Unfortunately wilting is so difficult to characterise, and is affected by so many external circumstances, that in any case it affords only a comparatively rough method of studying the "availability" of the soil water for the plant.

Micro-organisms require less moisture than plants, because they do not pump out water into the air, and it often happens that the production of nitrate and ammonia still continues in soils too dry to admit of plant growth.

Air Supply.

The figures given in Table XLIII. show that about 10 per cent. of the volume of a normally moist soil is occupied by air, but this volume

TABLE XLIV.—COMPOSITION OF THE AIR OF SOILS, PER CENT. BY VOLUME.

Soil.	Usual Composition.		Extreme Limits Observed.		Analyst.
	Oxygen.	Carbon-dioxide.	Oxygen.	Carbon-dioxide.	
Arable, no dung for 12 months	19-20	0·9	—	—	Boussingault and Léwy (48).
Arable, recently dunged.	—	—	10	10	Boussingault and Léwy (49).
Pasture land . . .	18-20	·5-1·5	10-20	·5-11·5	Schloesing fils (246).
Arable, uncropped, no manure, sandy soil .	20·6	·16	20·4-20·8	·05- ·30	Lau (158) mean of determinations made frequently during a period of 12 months. Values at depths of 15 cm., 30 cm., and 60 cm. not widely different. (30 cm. values given here.)
Arable, uncropped, no manure, loam soil .	20·6	·23	20·0-20·9	·07- ·55	
Arable, uncropped, no manure, moor soil .	20·0	·65	19·2-20·5	·28-1·40	
Sandy soil, dunged and cropped (potatoes), 15 cm. . . .	20·3	·61	19·8-21·0	·09- ·94	
Seradella, 15 cm. . .	20·7	·18	20·4-20·9	·12- ·38	
Pasture land . . .	20·0	·8	19·4-20·7	·4-2·3	Russell.

(Atmospheric air contains 21 per cent. of oxygen and ·03 per cent. of CO_2.)

is perpetually varying inversely as the amount of water varies. These changes alone would lead to a renewal of the air supply in the soil, but other factors, diffusion, changes in pressure, air movements, etc., come in, making the gaseous interchange still more complete. At soil depths reached by plant roots—some 6 to 12 inches—the soil air presents no abnormal features: there is some accumulation of carbon dioxide,

because this gas diffuses out more slowly than water vapour, oxygen, or nitrogen, but the percentage volumes of oxygen and nitrogen are nearly the same as those of the atmosphere. Of course, if the air supply is cut off by an accumulation of water on the surface, the oxygen may fall considerably in volume, but this case is exceptional. At still lower depths the volume of carbon dioxide may rise above 1 per cent.[1]

As might be expected, the carbon dioxide is higher in amount in summer than in winter, and higher in grass land than in arable. It may rise considerably in grass land, or in land recently dunged.

The Temperature of the Soil.

The temperature of the surface layer of soil, which in turn determines the temperature of the lower layers, is the resultant of several different effects. The actual amount of heat reaching the surface is that portion of the sun's rays that passes unabsorbed through the atmosphere, and is therefore dependent on the climate. The intensity of distribution of the heat over the surface depends on the slope of the land, and is greater the more nearly the land lies at right angles to the midday rays: thus, in our latitudes a south slope is warmer than a north slope, so much as often to produce marked vegetation differences. Many of the rays may be intercepted by vegetation, consequently land densely covered by plants is cooler and moister than bare land; advantage is often taken of this fact in tropical countries to protect soil from intense evaporation by the growth of "shade" crops. Of the rays that do finally reach the surface not all are absorbed, an unknown fraction being reflected back again into space: although no actual measurements have been made, the loss from this cause is probably greater on a white chalky soil than on a black humus soil.

The extent to which a given quantity of absorbed heat raises the temperature of a soil depends on its specific heat and this again on its water content. Dry soil has a specific heat of 0·2, while wet soil has a specific heat approximating more closely to 1, hence a dry soil will attain a higher temperature than a moist one. It commonly happens that the surface layer of the soil is hotter than the air, especially on a sunny day.

As a result of the interaction of these factors marked temperature variations occur over comparatively small areas of soil, being produced by differences in aspect, moistness, vegetation cover, looseness and so on. Illustrations are afforded in Table XLV. These variations are,

[1] Pettenkofer's determinations at Munich at depths 1½-4 m. below the surface are published in *N. Rep. Pharm.*, 1873, xxi., 677-702, and abstracted in *Journ. Chem. Soc.*, 1873, 361, and 1874, 26.

however, mainly confined to the surface layer; the passage of heat through the soil is slow and consequently the fluctuations at a depth of 3 inches are less marked, especially in dry, loose soils. The thermal conductivity of a soil is increased by moistening and by compacting.

For ordinary working purposes the following summary will be found useful:—

(1) A south slope is warmer than a north slope.

(2) Bare land is warmer than land covered with vegetation, excepting during winter months.

(3) Soil exposed to the sun's rays is often hotter than the air, and is subject to considerable temperature variations which, however, only slowly affect layers 3 or more inches deep.

(4) Moist soil, being a better conductor than dry soil, is much more uniform in temperature.

(5) At a depth of 4 to 12 inches soil is generally a little cooler than the air in summer, and warmer in winter.

Continuous records over periods of some months have been published by Wollny (319) and by Thiele (282). English data are rather scanty and generally refer only to 6 inch or 12 inch readings; they have, however, been collected and worked up by Mawley and by Mellish.[1]

TABLE XLV.—TEMPERATURES OF SOIL AT DIFFERENT DEPTHS UNDER VARYING CONDITIONS. RUSSELL.

Effect of Weather.

	Air Temp.	Temperature of Bare Soil. Untouched.			Surface Stirred by Hoes.		
		½ inch.	3 inch.	6 inch.	½ inch.	3 inch.	6 inch.
Hot sunny day, 20th June, 1910	30°	35°	30·5°	27°	31·5°	29·8°	26·5°
Cold cloudy day, 27th June, 1910	18°	17·5°	16·7°	15·8°	17°	16·3°	15·5°

Effect of Vegetation.

	Warm Weather, 5th Oct., 1910, Air Temperature, 17°.			Cold Weather, 4th Jan., 1911, Air Temperature, 5·5°.		
	½ inch.	3 inch.	6 inch.	½ inch.	3 inch.	6 inch.
Bare soil	17°	16·7°	15·5°	3°	2·5°	2·5°
Soil covered with living vegetation (grass land)	15·5°	15°	14·5°	3°	3°	3°
Soil covered with dead vegetation (mulched land)	15·5°	15°	14·5°	2·5°	2·0°	2·0°

[1] See *Quart. Journ. Roy. Meteor. Soc.*, 1899, xxv., 238-65.

Food Supply.

In spite of numerous investigations our knowledge of the plant food in the soil is very limited. On physiological grounds it is supposed that the whole of the nutrient material coming from the soil enters the plant in the dissolved state, but whether the actual soil solution is all the plant gets, as Whitney and Cameron suppose (see p. 76), or whether the carbon dioxide respired from the roots[1] effects the solution of more material than is already dissolved, has not been ascertained. The soil solution may safely be regarded as the minimum food supply, which is reinforced to an unknown extent by the soluble substances in the soil. All attempts to get any further have broken down, partly because the soil solution cannot be separated and subjected to examination (p. 63), and partly because the soil compounds cannot be sharply divided into two groups, one soluble and the other insoluble.

Nitrogen nutrition presents a tolerably simple case because plants growing on cultivated soils probably absorb all their nitrogen as nitrates, which are readily and completely dissolved by water, whilst plants in undisturbed soil—grass land, etc.—probably utilise ammonium compounds as well. Potassium and phosphorus nutrition present greater difficulties because very little is known about the compounds of these elements in the soil. This particular problem is of such technical importance that it has been necessary to do something empirically, and by common agreement the small fraction of the phosphorus and potassium compounds soluble in dilute acids is called "available" food material, while the rest is said to be "unavailable".[2] Here, however, the agreement ends, for no two dilute acids give the same results and no two Associations of Agricultural Chemists recommend the same dilute acid. Dyer's 1 per cent. citric acid (91, 92) is adopted in Great Britain, and its use has been justified by Wood's investigations (320 and 321). N/200 hydrochloric acid has been recommended in the United States, 2 per cent. hydrochloric acid by Nilson in Sweden, aspartic acid in Hawaii, and so on. The results obtained by different acids are shown in Table XLVI.

[1] At one time it was supposed that special acids were excreted by plant roots to dissolve insoluble food materials in the soil. This idea, which was a survival of the mediæval view that plants are wholly analogous to animals, persisted into our own times, but has been shown to be untenable by Czapek.

[2] Daubeny (78) originated this distinction, using the terms "active" and "dormant".

TABLE XLVI.—AMOUNTS OF K_2O AND P_2O_5 EXTRACTED BY ACIDS FROM ROTHAMSTED SOILS, PER CENT. OF DRY SOIL. HALL AND PLYMEN (117).

K_2O.	Strong HCl.	Dilute Acids Equivalent to 1 per cent. Citric Acid.			
		Citric Acid.	HCl.	Acetic Acid.	Carbonic Acid.
Broadbalk unmanured	0·380	0·0043	0·0147	0·0082	0·0111
" minerals only	0·463	0·0458	0·0522	0·0307	0·0215
" dung	0·453	0·0400	0·0684	0·0451	0·0380
P_2O_5.					
Broadbalk unmanured	0·114	0·0080	0·0021	0·0011	0·0005
" minerals only	0·228	0·0510	0·0360	0·0098	0·0058
" dung	0·209	0·0477	0·0224	0·0166	0·0095

Even strong hydrochloric acid only dissolves a part of the potash and phosphoric acid, the remainder not coming out till after treatment with hydrofluoric acid.

The different action of the various dilute acids has been adduced as evidence of the existence in soils of a considerable number of phosphorus and potassium compounds of varying degrees of solubility, but no such assumption is necessary. It more probably represents the division of these compounds between two solvents, the weak acid and the colloidal complex in which they are present in the soil (see p. 76).

More definite information can be obtained about the nitrogen compounds. The amount of ammonia and of nitrate can be ascertained to any desired depth. On cultivated land the amount is not generally more than enough for one year's crop, any balance being liable to be washed out in winter, so that the plant depends in spring on the activities of the decomposition processes for a regular supply of nitrogenous food. It is this circumstance that accounts for the marked retardation of plant growth in spring when the soil is wet and cold, especially after a wet winter when the washing-out process is complete, and it further accounts for the remarkable benefits produced by even small additions of nitrate of soda to the soil at this period.

In dry regions the accumulation of plant food and other soluble decomposition products in the soil may be too great to admit of plant growth, and bare patches or regions arise known as "alkali soils" from the circumstance that sodium and potassium carbonates are often present. In wetter climates the soluble substances tend to be washed out more completely, but notable quantities often persist in heavy clay soils, especially where the drainage is bad, and may produce injurious effects on vegetation.

In all discussions of the plant food in soils it is assumed that the *only significant plant nutrients are nitrates, phosphates, sulphates and* salts of potassium, calcium, magnesium and iron, commonly called the "essential" plant foods. Perfect plants can be raised in water cultures containing only these substances. Reference to Fig. 5 (p. 39), however, shows that productiveness is not always maintained indefinitely simply by supplying these salts, and not nearly so well as when the complex farmyard manure—excreta, litter, etc.—is used. It is known also that certain other compounds besides the "essential" foods may increase plant growth (p. 45). Further, Russell and Petherbridge have shown that on heating soil to 100° something is formed that stimulates root production to a remarkable degree. Are these effects the results of nutrition or of stimulation? Are the manganese, lithium, etc., compounds and the beneficial soil constituents indispensable nutrients of which only traces are required, or are they, as Armstrong expresses it, "condimental" foods? The evidence is not very decisive, and may be made to serve either hypothesis, but in many cases Armstrong's view is the simpler. At any rate there is evidence that our view of the plant nutrition in the soil has hitherto been too narrow and ought to be widened.

The Nature of the Medium on which the Soil Life Goes On.

It is a mistake to suppose—and this point cannot be too strongly emphasised—that the medium on which the soil organisms live and which is in contact with the plant roots, is the inert mineral matter that forms the bulk of the soil. Instead the medium is the colloidal complex of organic and inorganic compounds, usually more or less saturated with water, that envelops the mineral particles; it is, therefore, analogous to the plate of nutrient jelly used by bacteriologists, while the mineral particles serve mainly to support the medium and control the supply of air and water and, to some extent, the temperature. As yet our knowledge of the detailed composition of this medium is very slight (see Chap. III.); but we shall get a very false idea of the conditions of life in the soil unless we recognise the main fact of its existence and fundamental significance.

Are Toxins Present in the Soil?

A persistent idea that one crop may poison another is current among practical men. Early in the last century De Candolle formulated the hypothesis that plants excrete from their roots toxins that remain in the soil for some time and injure other plants of the same

species, but not necessarily plants of different species. He thus explained the well-known fact that a rotation of crops is more effective than a system of continuous cropping; in a rotation the toxin excreted by a particular crop is innocuous to the succeeding crops and disappears from the soil before the same plant is sown again.

The hypothesis was tested in a classical research by Daubeny at Oxford (78), but could not be justified. Eighteen different crops were grown continuously on the same plots, and the yields compared with those obtained when the same crops were shifted from one plot to another, so that no crop ever followed another of the same kind. No manure was supplied. The results showed a gradual decrease in the yield in almost every instance, and the decrease was generally greater when the crop was repeated year after year on the same plot than where it was shifted from one to another. Nevertheless the difference between the yields in the two cases was not sufficient to justify any assumption of the existence of a toxin, except perhaps in the case of *Euphorbia lathyris*; in the other seventeen cases it was attributed to the more rapid removal from the continuous plots of the mineral nutrients required by the plant. This explanation was supported by analyses of the plant ash and of the soil—analyses which led to the important distinction between "available" and "unavailable" plant food.

Pot experiments made by the writer at Rothamsted have led to the same conclusions. Six crops of rye were grown in succession in sand to which only nutrient salts were added so as to maintain the food material at a constant amount. A seventh crop was then taken and at the same time a crop was grown on perfectly fresh sand, on which no crop had ever grown before, but which was supplied with an equal amount of the same nutrient salts. There was no significant difference in the two crop yields. A similar experiment was made with buckwheat, another with spinach, and a parallel series was made in soil cultures. In all cases but one the result was the same; the 1910 weights were as follows:—

	Sand Cultures.			Soil Cultures.		
	Weight of dry matter found, grams (mean of 4 pots).			Weight of dry matter found, grams (mean of 4 pots).		
	Rye.	Buckwheat.	Spinach.	Rye.	Buckwheat.	Spinach.
Cropped six times previously	30·4	5·4	33·3	26·4	23·9	20·0
Fresh sand or soil . .	31·3	13·5	29·5	27·1	25·2	20·8

Both sand and soil contained 2 per cent. of calcium carbonate.

If either the rye, buckwheat or spinach excreted any toxin the amount accumulating during the growth of six successive crops was insufficient to cause any appreciable depression in yield in the next crop; the exceptional result given by buckwheat in sand could not be confirmed.

These and similar experiments show that no lasting toxic effect is produced by any of the crops studied, and they rule out any toxin hypothesis as an explanation of the advantages of rotations[1] where there is always a lengthy interval between the crops. They do not, however, show that there is no transient effect, and they are thus quite consistent with some remarkable observations by Pickering on the effect of grass on apple-trees (227). It was found at Woburn—and the observation has since been confirmed elsewhere—that the effect of sowing grass round apple-trees is to arrest all healthy growth and absolutely stunt the tree. The leaves become unhealthy and light coloured, the bark also becomes light coloured, while the fruit loses its green matter and becomes waxy yellow, or brilliant red. Where the grassing was done gradually the trees accommodated themselves somewhat to the altering conditions, but never grew so well as when grass was absent.

This effect might have been due to various causes: changes in aeration, temperature, water supply, food supply, or physical condition of the soil, but careful experiments failed to show that any of these factors came into play. Covering the soil with cement excluded air at least as thoroughly as grass, and yet did not produce the grass effect, nor was it suppressed by wet seasons, liberal watering, or a supply (in pot experiments) of sufficient water or nutrient solution to keep the soils of grassed and ungrassed trees equally moist, or equally well supplied with food. On the other hand, the grass effect was produced when perforated trays of sand containing growing grass were placed on the surface of the soil in which trees were growing, so that the washings from the grass went straight down to the tree roots. There seemed no possibility of the grass roots in the trays abstracting anything from the soil, and the only explanation appears to be that a toxin is excreted by the grass. Such a toxin, however, must be very readily decomposed, because no toxic properties could be discovered by laboratory tests either in soil that had been removed from the grass roots or in the washings from the above-mentioned trays. These results show that we must be prepared to consider possible toxic effects of one plant on another *growing alongside of it*, and they raise the question whether such effects may not play a part in determining plant associations.

[1] Some curious problems are thus left unsolved, some of which are discussed more fully by the author in *Science Progress*, July, 1911, p. 135.

Pickering's results agree with the hypothesis already put forward by Whitney, and developed by him and Cameron, Schreiner (306, 68, 249, etc.) and their colleagues at the Bureau of Soils, Washington. Certain soils are supposed to contain toxins, which are not necessarily plant excretions, but may arise by decomposition of organic matter in the soil. The genesis of this hypothesis is interesting. Reference has already been made to Whitney's view that the soil solution furnishes the food of plants and is of the same composition and concentration in all soils, from which it follows that infertility of any soil cannot be due to lack of food. But in certain cases this infertility is transmitted to the aqueous extract of the soil, and must, therefore, arise from some soluble toxin. As an example Whitney and Cameron (305) selected two Cecil clays of very different productiveness but of identical chemical and physical constitution, prepared aqueous extracts and used them as culture solutions for wheat seedlings. The extracts contained in parts per million:—

	NO_3.	PO_4.	K.	Ca.
Good soil . . .	3·2	1·6	3·6	3·2
Poor soil . . .	3·5	1·6	2·0	2·8

and were thus identical in their content of plant nutrients; they were also both neutral. Yet they produced very different effects on the wheat seedlings: the "good soil" extract caused a larger and healthier development of root and a somewhat better development of leaves. In other cases it has been found that growth in extracts of poor soils is even worse than in distilled water. The productiveness of the extract could be raised, according to Livingstone (178), by dilution, shaking with calcium carbonate, precipitated ferric or aluminium oxide, animal charcoal, or soil; results which are explained by supposing that these agents precipitate a toxin. Addition of fertilisers, and especially of an aqueous extract of farmyard manure, improved the solution; these substances also were supposed to precipitate the toxin.

A double set of experiments was therefore began by Schreiner and his colleagues: a careful search was made in the soil for such organic compounds as could be identified (see p. 72); and the effect of these and similar compounds on plant growth was studied by elaborate water cultures. Considerable attention has been devoted to dihydroxystearic acid. This substance is toxic to plants in water culture, and is almost invariably present in infertile soils, especially such as are badly

drained, badly aerated, too compact, and deficient in lime (251); soils, in short, that in England are called "sour".

On the other hand, Russell and Petherbridge could not obtain any aqueous extract toxic to plants from greenhouse "sick" soils. These soils, however, are rich in organic matter, in plant food, and in calcium carbonate.

The present position may briefly be summed up as follows: there is no evidence of the presence of soluble toxins in normally aerated soils sufficiently supplied with plant food and with calcium carbonate, but toxins may occur on "sour" soils badly aerated and lacking in calcium carbonate, or on other exhausted soils. There is no evidence of any plant excretions conferring toxic properties on the soil, but the Woburn fruit tree results show that a growing plant may poison its neighbour.

Bacterio-toxins.—Several observers, including Greig-Smith (113), Bottomley (42) and others, have claimed to find soluble bacterio-toxins in soils. Russell and Hutchinson, on the other hand, obtained wholly negative results, and concluded that soluble bacterio-toxins are not normal constituents of soils, but must represent unusual conditions wherever they occur. But the possibility of the existence of toxins insoluble in water still remains.

The Simplification of the Soil Population—Partial Sterilisation of Soil.

The earliest observations that soil is altered by an apparently inert antiseptic arose out of attempts to kill insect pests in the soil by means of carbon disulphide. This substance, which for fifty years has been known as an insecticide, was used in 1877 by Oberlin (219), an Alsatian vine-grower, to kill phylloxera, and by Girard (106) in 1887 to clear a piece of sugar-beet ground badly infested with nematodes. In both cases the subsequent crops showed that the productiveness of the soil had been increased by the treatment.

The first piece of scientific work came from A. Koch in 1899 (150), who, working with varying quantities of carbon disulphide, concluded that it stimulates the plant root to increased growth. Four years later Hiltner and Störmer (136) showed that the bacterial flora of the soil undergoes a change. The immediate effect of the antiseptic was to decrease by about 75 per cent. the number of organisms capable of developing on gelatin plates; then as soon as the antiseptic had evaporated, the numbers rose far higher than before, and there was also some change in the type of flora. It was argued that the in-

creased numbers of bacteria must result in an increased food supply for the plant, and it was claimed that the new type of flora was actually better than the old, in that denitrifying organisms were killed, nitrogen-fixing organisms increased, and nitrification only suspended during a period when nitrates were not wanted and might undergo loss by drainage. In a later publication Hiltner (137) shows that other volatile or easily decomposable antiseptics produce the same effect. The important part of this work is unquestionably the discovery that the organisms in the treated soils ultimately outnumber those in the original soil. The hypothesis that the new type of flora is actually more efficient than the old rests on less trustworthy evidence, and has indeed been modified in some of its details by Hiltner himself.

The effect of heat on the productiveness of the soil was first noticed by the early bacteriologists. It had been assumed that heat simply sterilised the soil and produced no other change, until Frank (99) in 1888 showed that it increased the soluble mineral and organic matter and also the productiveness. Later work by Pfeffer and Franke (226) and by Krüger and Schneidewind (156) showed that plants actually take more food from a heated than from an unheated soil. Heat undoubtedly causes decomposition of some of the soil constituents quite apart from its effect on the soil flora.

Experiments by Russell and Darbishire (239) showed that the rate of oxidation was considerably reduced after the soil had been heated to 130° C., but was increased by treatment with small quantities of volatile antiseptics, and more than doubled after heating to 100° C. The bacterial activity is therefore increased and consequently the amount of decomposition. The increased quantity of plant food thus formed is shown by the amounts taken up by the plant. Table XLVII. contains a typical series of results:—

TABLE XLVII.—WEIGHT AND COMPOSITION OF CROPS GROWN ON PARTIALLY STERILISED SOILS. RUSSELL AND DARBISHIRE.

	Dry Weight of Crop.	Percentage Composition of Dry Matter.			Weight of Food taken by the Plant from Soil, grams.		
	Grams.	N.	P_2O_5.	K_2O.	N.	P_2O_5.	K_2O.
Buckwheat.							
Untreated soil	18·14	2·75	1·87	5·62	·499	·339	1·019
Soil treated with carbon disulphide	23·27	3·15	2·34	5·97	·733	·344	1·389
Mustard.							
Untreated soil	15·88	2·30	1·00	4·20	·367	·159	·668
Heated soil	24·33	4·43	2·08	5·02	1·077	·506	1·221

Further investigations by Russell and Hutchinson (240) showed that the most striking chemical changes that set in after partial sterilisation are the cessation of nitrification and an accumulation of ammonia much in excess of the sum of the ammonia and nitrate in the untreated soil.

TABLE XLVIII.—AMMONIA AND NITRATE ACCUMULATING IN A SOIL KEPT TWENTY-THREE DAYS AT ABOUT 15° C. IN A MOIST CONDITION; PARTS PER MILLION OF DRY SOIL.

	Nitrogen present as Ammonia.		Nitrogen present as Nitrate.		Total Nitrogen present as Ammonia and Nitrate.		
	At beginning.	After 23 days.	At beginning.	After 23 days.	At beginning.	After 23 days.	Gain in 23 days.
Untreated soil . . .	1·8	1·7	12	16	13·8	17·7	3·9
Soil heated 2 hours to 98° C.	6·5	43·8	13	12	19·5	55·8	36·3
Soil treated with toluene, which was then evaporated	5·0	27·8	12	12	17·0	39·8	22·8
Soil treated with toluene, which was not removed .	7·2	14·5	11	10	18·2	24·5	6·3

The accumulation of ammonia might be due either to an increased production in the treated soils or to the removal by the treatment of some agent, other than the nitrifying organisms, which is always consuming ammonia. The second supposition falls to the ground because, when small quantities of ammonium salts are added to untreated soils, the whole of the added nitrogen is recovered as ammonia and nitrate. Hence it is concluded that the treatment had induced an increased production of ammonia.

Several considerations show that the production of ammonia subsequent to the small initial gain on heating, or treating with toluene, is

TABLE XLIX.—NUMBERS OF BACTERIA AND AMOUNTS OF AMMONIA PRODUCTION IN PARTIALLY STERILISED SOILS.

	Numbers of Organisms per gram of Dry Soil, in Millions, Gelatin Plate Cultures.			Ammonia produced in 9 days, in parts per million of Dry Soil.
	At beginning.	After 9 days.	Increase during 9 days.	
Untreated soil . . .	6·7	9·8	3·1	0·7
Soil heated to 98° . . .	·0003	6·3 [1]	6·3 [1]	3·2 [1]
Soil treated with toluene, which was subsequently evaporated	2·6	40·6	38·0	17·1
Soil treated with toluene, which was left in	2·3	2·6	0·3	5·5

[1] After four days, nine days' count lost by plates liquefying.

mainly the work of micro-organisms. The curves belong to the type associated with bacterial, rather than purely chemical, change. Soil which has been heated to 125° C. (at which temperature all organisms are killed) shows no increase in ammonia-content after the first small gain. There is no rapid period of gain if enough toluene is left in to inhibit bacterial action, nor if the water supply is insufficient. Further, the numbers of bacteria increase *pari passu* with the amount of ammonia; and as addition of ammonium salts to untreated soil led to no such increase as is observed here, it was concluded that the increased production of ammonia was due to the increased numbers of bacteria.

The new flora arising after partial sterilisation was found to be more active than the original flora in effecting the decomposition of nitrogenous organic matter, such as peptone, and in hydrolysing urea. But there is no evidence that the individual species surviving the treatment have become more active—on the contrary organisms isolated from the partially sterilised soils proved less active than others of the same kind from the untreated soil. Nor can the difference in the rate of ammonia production be attributed to a change in the type of bacterial flora. Examination of the gelatin plates showed that the flora establishing itself in the heated soil is altogether different from that originally present; while the flora of the soil treated with toluene did not appear to have altered very much. The curves showing the amount of ammonia produced in the soil treated with toluene and in the heated soil are very much alike, but the bacterial flora of the soils is very different; the curves for the untreated soil and the soil treated with toluene are fundamentally different, whilst the bacterial flora is not. Lastly, reintroduction of bacteria from the untreated soil to the partially sterilised soil led to still further increases both in bacterial numbers and in the rate of decomposition, whilst addition of bacteria from partially sterilised to untreated soils had little or no effect.

The experiments, therefore, indicate that the increased production of ammonia in the partially sterilised soil is due to the increased numbers of the bacteria rather than to any other cause; the problem reduced itself to finding out why the bacteria can increase so much more rapidly in the partially sterilised than in the untreated soils. No evidence could be obtained that partial sterilisation produced any sufficient increase in bacterial food to account for the results, it appears rather that the untreated soil contained some factor detrimental to bacteria and put out of action by heat or antiseptics. All attempts to find a soluble toxin in the untreated soil failed. The factor appeared to be biological and could be reintroduced into the partially sterilised soil

by inoculation. Addition of *small* quantities (0·5 per cent.) of untreated soil, or of a filtered aqueous extract of the soil containing bacteria, considerably *increased* the total number of organisms, while addition of *large* quantities (5 per cent.) of untreated soil led to a considerable reduction. The depressing effect was not shown at once, as the effect of a toxin should have been, but only after the lapse of some time.

TABLE L.—EFFECT OF REINFECTING UNTREATED SOIL INTO PARTIALLY STERILISED SOIL.

	Gain in Ammonia and Nitrate in 57 days.	Numbers of Bacteria in millions, per gram of Dry Soil.		
		After 20 days.	After 38 days.	After 61 days.
Toluened soil alone . . .	24·3	28·0	31·8	60·1
" " + extract from untreated soil . . .	43·7	61·3	45·2	166·6
Toluened soil + 5 per cent. untreated soil	20·3	32·0	46·9	48·0

The factor does not operate unless sufficient moisture is present, and it reaches its maximum development in moist, warm soils well supplied with organic matter and bacteria—such as sewage farm soils and greenhouse soils. It does not appear to be bacterial, since its effects do not show in the aqueous extract of the soil; and it does not come into evidence in the partially-sterilised soils as the bacteria develop. Search was, therefore, made for larger organisms, such as infusoria, amœbæ and other protozoa. None were found in the heated soil, and only small ciliated infusoria in the soil treated with toluene. But the untreated soil contained a variety of them, and the evidence at present available goes to show that such large organisms constitute the factor, or one of the factors—for there may be others—limiting bacterial activity, and, therefore, fertility in ordinary untreated soils.

The micro-organic flora of an ordinary soil thus appears to be very mixed and includes a wide variety of organisms performing very different functions. Saprophytes, parasites attacking plants and apparently also living on and decomposing organic matter, and large organisms inimical in various ways to bacteria all seem to be present. The action of the saprophytes tends to increase the fertility of the soil, *e.g.*, they produce ammonia, fix nitrogen, and so on. On the other hand, the parasites are obviously harmful, while the phagocytes and similar organisms are detrimental to fertility because they limit the number of bacteria, and, therefore, the rate at which ammonia is produced.

Between these classes of organisms there is an equilibrium under natural conditions. When, however, toluene is added or when the soil

is heated to 98° C. for a short time, or dried at lower temperatures (*e.g.* 40°) for a longer time, the phagocytes are killed, but not the bacterial spores. On removing the toluene and moistening the soil, the spores germinate, and the resulting organisms multiply with great rapidity, since they now have a clear field. The individual species may be less virulent than the old races, but they more than make up for any deficiency in this direction by their enormously increased numbers. The rate of decomposition is considerably hastened and a larger amount of ammonia is produced, so that the fertility of the soil is increased. Some, if not all, of the parasites are also killed, and the plant has a better chance of development.

The Action of the Plant on the Soil.

The plant reacts in several ways on the soil. It takes up nitrates and other substances, thus preventing too great an accumulation of soluble material in the soil. It also effects a certain amount of decomposition. Water cultures in which plants are growing are known to become alkaline; the explanation offered is that the plant takes up the acid radicle of the sodium nitrate and leaves behind the base, which immediately appears as the carbonate. Hall and Miller (118) have obtained evidence of a similar action in the soil, the calcium nitrate formed during nitrification being converted into calcium carbonate while the nitrate radicle is taken by the plant. These effects are favourable to micro-organisms; others are unfavourable, such as the removal of moisture by the plant and the evolution of carbon dioxide from the roots.

CHAPTER VI.

THE SOIL IN RELATION TO PLANT GROWTH.

WE are now in a position to summarise the effect of the various soil conditions on the growth of plants. The soil serves several functions; it affords a more or less continuous supply of food and water, it regulates the temperature and provides anchorage for the roots without interfering too much with the air supply. The extent to which any of these things is done depends on the nature of the particles and therefore varies from soil to soil. As the requirements of plants also vary in degree, the different soil types have come to possess their own flora made up of those plants that tolerate the conditions better than other possible competitors, and on cultivation they show different agricultural characteristics.

In discussing the relationship between plant growth and the soil it is necessary to take into account not only the *intrinsic* properties of the soil due to the nature of its constituent parts, but the *extrinsic* properties impressed by topographical and climatic factors. A certain indefiniteness thus becomes unavoidable, because none of the latter can be expressed in exact measurements. This point is well illustrated by the water supply. The amount of water in the soil at any time is the balance of gains over losses. The gains depend on the rainfall (*i.e.*, climate), and on the amounts of water derived by drainage from higher land (*i.e.*, topographical position), or by surface tension from the subsoil; the losses depend on the extent to which the subsoil facilitates drainage and on the rate of evaporation, which in turn depends on the temperature, the exposure of the soil, the velocity of the wind and the mode of cultivation. Five factors have therefore to be considered: (1) the nature of the soil particles, (2) the amount and distribution of the rainfall, (3) the position of the soil in relation to the land round about it, its aspect, shade, and any other factors affecting its relative temperature and water supply, (4) the depth of the soil, (5) the nature of the subsoil, especially its perviousness to air, water and plant roots. Any of these factors may, within certain limits, dominate the rest and profoundly affect the flora and the agricultural value; thus

a sandy soil may, without any change in type, be a dry and barren heath if underlain near the surface with rock or gravel, a highly fertile fruit or market-garden soil if sufficiently deep, or a stagnant marsh giving rise to peat if so situated that water accumulates and cannot drain away.

No sharp division can be drawn between the intrinsic and extrinsic properties. The significant units in the soil that determine its intrinsic properties are the compound particles made up of the ultimate mineral particles—clay, silt, sand, etc.—together with calcium carbonate and organic matter derived from plant remains. Now the nature and amount of the organic matter are greatly influenced by the extrinsic conditions—the temperature and water supply—that have obtained in the past. Moisture, warmth and aeration favour the development of a succulent vegetation which sheds easily decomposable leaves and stems on to the soil; earthworms and bacteria can now flourish and produce the normal decomposition products that go to make up "mild humus" and a fertile soil. Dryness necessitates a narrow-leaved xerophytic vegetation, the leathery fragments of which mingle with the soil, but afford a very indifferent medium for the growth of earthworms and bacteria, so that little decomposition goes on and a barren sand results. Wetness and lack of aeration necessitate special vegetation and decomposition agents, and there may result a "mild humus" if sufficient calcium carbonate is present to determine a calcicolous flora, or an "acid humus" in the contrary event. Thus the soil is very much the result of circumstances; its character is determined in part by the rock from which it was derived, and in part by subsequent events, particularly the temperature and water supply it happened to obtain, in other words, its climate. A given set of mineral particles may give rise to soils wholly different in agricultural value and in natural flora.

Further, the farmer has discovered how to build up these compound particles by cultivation and thus change to a very great extent the relation of the soil to the plant: the process consists in adding dung, or ploughing in green crops, adding lime, exposure to frost, and skilful (but wholly empirical) cultivation, and, although not very rapid, it takes only a few seasons to accomplish.

But while the ultimate mineral particles do not entirely control the relationships of the soil to vegetation they fix the limits within which these relationships may vary and beyond which they cannot pass. Farmers recognise five great divisions: clays, loams, sands, chalky soils and soils rich in organic matter, all shading off into one another and without sharp lines of demarcation, but representing classes of

soil that cannot be changed one into the other by any cultivator's artifice.

Calcareous Soils.—The simplest case is presented by soils where the calcium carbonate exceeds about 10 per cent. and dominates every other constituent, becoming the controlling factor in determining the soil properties. The conditions here seem to be extraordinarily well suited to plant and animal life. Bacteria are numerous and active, rapidly oxidising organic matter. Hosts of animals, wireworms, earthworms and others live in the grass land, and even get into the arable land, honeycombing the soil with their passages, puffing it up or "lightening" it considerably, and encouraging the multiplication of moles. Rabbits abound in dry places. Vegetation is restricted on thin exposed soils, but becomes astonishingly varied where there is sufficient depth of soil and shelter to maintain an adequate water supply. Ash is the characteristic tree in the north and beech in the south of England, and there is a great profusion of shrubs—guelder rose, dogwood, hawthorn, hazel, maple, juniper; and especially of flowering plants—scabious, the bedstraws, vetches, ragwort, figwort. Still more remarkable, perhaps, is the fact that a few plants—the so-called calcifuges—do not occur. Where the amount of calcium carbonate becomes too high plants tend to become chlorotic; Chauzit's analyses showed that vines suffered badly when 35 per cent. or more was present, but not when the amounts fell to 3 per cent.[1]

The reason for these special features is not clear, but is probably not to be found in any one factor. The plants do not require such high amounts of calcium carbonate because they will wander on to an adjacent loam; even the absence of the calcifuges cannot always be attributed to a supposed toxic effect of calcium carbonate because in other regions, or in pot experiments, some at any rate of them may be found growing in its presence. In a prolonged investigation near Karlstadt, Kraus (155) found no plant occurring exclusively on soils with even approximately equal content of calcium carbonate, although some preferred more, *e.g. Festuca glauca, Teucrium montanum* and *Melica ciliata*, while others preferred less, *e.g. Brachypodium pinnatum, Kœleria cristata*, and *Hieracium pilosella*. True chalk plants were found on the adjoining sand, especially when some calcium carbonate was present, although the true sand plants did not wander on to the chalk. In such cases of displacement or "heterotopy" it was shown that the general physical conditions of the two locations were similar in spite of their

[1] See *Revue de Viticulture*, 1902, xviii., 15, and also Molz, *Centr. Bakt. Par.*, Abt. ii., 1907, xix., 475.

wide difference in chemical composition. Kraus, therefore, argues that the true chalk plants inhabit chalk soils not because they need much calcium carbonate, but because they find there the general physical and chemical conditions they require.

The fact that a calcareous rock lies beneath is no proof that the soil itself is calcareous: on the contrary the soil may often contain practically no calcium carbonate, either because it has become decalcified by rain, or because it really represents some deposit of wholly extraneous origin.

The agricultural value of chalk soils depends very largely on their depth, and is much greater in valleys where the soil and water collect than on the higher ground where the soil is thinner. The two defects most in need of remedy are the lack of organic matter and the tendency to become light: these are met by additions of dung or other organic manures, by rolling and cultivating with heavy instruments, and above all by feeding animals on the land with the crops actually growing there and with purchased food, a process known as "folding". Heavy wooden ploughs are still in use, and until recently were worked in many places by large teams of heavy oxen. Sheep are by far the most suitable animals to be fed on the land, and they form the centre round which the husbandry of chalk districts has developed, indeed so important are they that each chalk region has evolved its own breed of sheep—South Downs, Hampshires, etc. As fertilisers potassic manures, especially kainit, are generally profitable, superphosphate is needed for turnips, and in wet districts basic slag is useful on the grass land. Skilful cultivation is always necessary, or the soil dries into hard, steely lumps that will not break down. And, lastly, the pre-eminent suitability of the chalk to plant and animal life has its disadvantages; no soils are more prone to carry weeds, turnip "fly," or wireworm. Skilful management is the keynote of success and it generally obtains, the bad farmers not usually surviving many seasons.

Black Soils or Humus Soils.—In these the organic matter dominates all other factors, but the case is more complex than the preceding, because several varieties of organic matter occur, giving rise to several types of soil. A sufficiently full description having already been given (pp. 65 *et seq.*) it is only necessary to mention the chief agricultural characteristics. Peat soils generally need drainage and addition of calcium carbonate and potassium salts; their agricultural possibilities are much investigated in Prussia where several million acres of moorland occur.

Fen soils, on the other hand, stand more in need of phosphates and respond well to superphosphates: they do not require lime. Potatoes

grow well and many other crops can be raised. The black soils of the Canadian prairies have been described by Shutt (264): under wheat cultivation they require no fertiliser; the similar Tchernozem of Russia and Hungary also carry practically nothing but wheat and receive little or no manure.

Clay Soils.—Clay soils are characterised by the presence of 20-50 per cent. of "clay" and similar quantities of silt and fine silt; in consequence of this excess of fine particles the size of the pores is so diminished that neither air nor water can move freely. Clay soils, therefore, readily become waterlogged and in time of drought may not sufficiently quickly supply the plant with water; in our climate, however, they are usually moist or wet. The high content of colloidal matter impresses marked colloidal properties: (1) the soil shrinks on drying and forms large gaping cracks which may be several inches wide and more than a foot deep; (2) it absorbs much water, a good deal still being held even when the soil appears to be dry; (3) it readily absorbs soluble salts, or parts of them, and organic substances. In addition the special clay properties are shown: plasticity and adhesiveness when wet, and a tendency to form very hard clods when dry. All these properties are much modified by calcium carbonate and intensified by alkalies; liquid manure (which contains ammonium carbonate) and nitrate of soda (which gives rise to sodium carbonate in the soil) are both to be avoided.

Clay soils have had rather a chequered agricultural history. Originally covered with oak forest and hazel undergrowth they were early reclaimed for agricultural purposes by draining, applications of lime,[1] and, later, of ground bones. Wheat and beans were the great clay crops, and in the early part of the last century, under the combined influence of high prices, large drainage schemes and artificial stimulus to enclosure, great areas came into cultivation so that now only little unreclaimed clay remains, excepting where the forest was preserved for hunting. Crops grew well but ripened late; a wet harvest was a terrible calamity. Bare fallowing was always necessary once in four years and any of the intervening years might, if wet, be lost by the difficulty of getting on the land to sow the crop. When the price of wheat fell in the 'eighties many of these soils went out of cultivation and became covered with a mixed growth of grass and weed, which was grazed by stock and gradually deteriorated as the old drains choked up and the land became more and more waterlogged. *Aira cæspitosa*, "bent" grass (*Agrostis vulgaris*), yellow rattle (*Rhinanthus Crista-galli*), and in dryer places the quaking grass (*Briza media*) and ox-eyed daisy

[1] *E.g.* see Gervase Markham, *Inrichment of the Weald of Kent*, 1683.

(*Chrysanthemum Leucanthemum*) are among the more obvious plants on these neglected fields; the only relics of the past are the field names and the high ridges or "lands" made years ago to facilitate drainage. But recently marked improvement has set in. Drainage is gradually being attended to, whilst additions of lime and phosphates (as basic slag) have markedly improved the herbage, favouring the development of white clover (*Trifolium repens*) and the pasture grasses, and crowding out the weeds. Potassic fertilisers are not usually needed. Only in the dry eastern counties has the old arable cultivation survived.

Sandy soils are formed of large silica particles deficient in colloidal matter, and therefore possessing little power of cohesion, or of retaining water or soluble salts. Hence they tend to be dry, loose, and poor in soluble substances—"hungry," the practical man calls them. Their behaviour towards vegetation depends very largely on their position, their depth, and the nature of the subsoil, these being the factors that determine the water supply to the crop. The water supply is usually satisfactory when the surface soil contains sufficient clay and not too much coarse sand and gravel, and rests on a deep subsoil containing rather more of the finer particles. It is a further advantage if other land lies higher and furnishes a supply of underground water. In such cases the land is nearly always cultivated; it yields early crops of high quality rather than heavy crops, the tendency to drought inducing early maturation, while the absence of stickiness makes sowing an easy matter at any time. Fruit, potatoes, and market-garden produce are often raised, and high quality barley is also grown. The winter feeding of sheep on the land is a common way of fertilising, but crops must be sown early, or the fertilising material is washed out unused, and the young roots have no time to strike into the subsoil before the surface layer dries out. High farming is the only profitable way of dealing with these soils; any carelessness in cultivation lets in hosts of weeds, such as poppies, knot-weed (*Polygonum aviculare*), spurrey (*Spergula arvensis*), sorrel, horsetail, convolvulus, creeping buttercup, and others. Crops should follow each other in rapid succession, any interval being a period of loss; under good management two or even three market-garden crops can be secured in the year, while in purely farming districts catch crops should always be taken. Organic manures are very necessary to increase the water-holding capacity: sheep-folding or green-manuring are, therefore, very desirable. Calcium carbonate is often needed and is better applied as ground chalk or limestone than as lime. Potassium salts are beneficial and may be added as kainit; nitrates often give remarkable results, but

phosphates are not usually needed because the soil conditions already tend to promote good root development. Only small quantities of manure must be added at the time, as the soil has little retentive power. Above all, no very costly scheme of manuring should be recommended till preliminary trials have shown its profitableness.

A soil underlain at a short distance below the surface by a bed of gravel, a layer of rock, or a "pan," is liable to be either parched or waterlogged, and its water supply is usually so unsatisfactory that cultivation is unprofitable. Under low rainfall the land becomes a steppe, under rather higher rainfall a heath, but the vegetation is always xerophytic, consisting of heather, ragwort, broom, etc., the trees being birch and conifers—the latter often planted in recent times. No method of cultivating these soils has ever been devised, and most of them still remain barren wastes, defying all attempts at reclamation. Two special cases have, however, yielded to treatment:—

1. When the layer of rock or the pan is only thin and is, in turn, underlain by a rather fine-grained sand, its removal brings about continuity in the soil mass and thus effects a great improvement in the water supply. The soil now resembles the fertile sands, and should be treated in the same way. A good example is afforded by Cox Heath, Maidstone (p. 140).

2. Where the gravel or rock is not too near the surface, systematic green manuring with lupines and other crops fertilised by potassium salts and calcium carbonate will often effect sufficient improvement to make cultivation profitable. Examples are afforded by the Schultz-Lupitz estate, Germany (255) and Dr. Edward's experiments at Capel St. Andrews, Suffolk. On such land an industrious cultivator may make a living but not a fortune.

Under favourable conditions recourse may be had to dressings of clay (as in Lincolnshire) or to warping (in the Fens).

Barren conditions also result when, by reason of a thin parting of clay or its low situation, water cannot run away but accumulates and forms a marsh. Reclamation in such cases is possible as soon as a way out has been found for the water.

Loams.—As the proportion of fine material in the soil increases and that of coarse material falls off, a gradual change in the character of the soil sets in, till finally, but without any sharp transition, a new type is reached known as a loam. The increase of fine material somewhat retards the movements both of air and of water, so that loams are characterised by a more uniform water content throughout the mass than sands. On the other hand loams show less tendency to become water-

logged or to allow plants to become parched in very dry weather than clays. The soil decompositions proceed normally, rapidly producing plant food, with little tendency to "sour"[1] or other abnormal conditions so long as sufficient calcium carbonate is present. In consequence most plants will grow on loams, even some of those supposed to be specially associated with some other soil type. Thus, where a chalk and a loam soil meet, it is not uncommon to find the chalk plants, *e.g.* traveller's joy (*Clematis Vitalba*), guelder rose, etc., wandering on to the loam and it is much more difficult to find the line of separation of the soils than where the chalk abuts on to a sand or a clay. For the same reason loams allow of very wide choice in the systems of husbandry, and, as they become very fertile under good management, they are usually in this country all cultivated. Closer observation over a limited area shows, however, that a given class of loam is more suited to one crop than to another; the ecologist recognises differences in the sub-associations or facies, and the practical man will distinguish between a potato soil, a barley soil, a wheat soil, etc.; distinctions due no doubt to water and air relationships, and arising from differences in the compound particles. Unfortunately no method of investigating the compound particles has yet been devised, and a study of the ultimate particles by a mechanical analysis is alone possible. But even though the differences are thus attenuated they can still be traced, as shown by the analyses in Table LI. of soils in Kent, Surrey, and Sussex, known to be well suited to the particular crops.

TABLE LI.—MECHANICAL ANALYSES OF SOILS WELL SUITED TO CERTAIN CROPS IN THE SOUTH-EASTERN COUNTIES; LIMITS OF VARIATION. HALL AND RUSSELL (123).

	Potatoes.	Barley.	Fruit.	Hops.	Wheat.	Waste Land.
Fine gravel	0·1-3	0·2-2·5	0·3-2·3	0·3-2·3	0·4-6	0·1-7
Coarse sand	2-47	1-53	0·8-9·5	0·7-9·5	0-13	0·3-69
Fine sand	23-68	20-45	30-55	25-39	15-31	18-64
Silt	3·5-21·4	5-33	13-44	20-45	11-35·5	2·5-20
Fine silt	5-9	3·5-16·4	6-11	6-11	9·5-24	2-10
Clay	5·5-12·6	4-19	10·5-14·6	11·5-15	13-24	0·2-6

Low amounts of clay and fine silt, and high amounts of coarse sand whenever the clay begins to approach 12 per cent., characterise the potato soils; these are the most porous of the series, allowing free drainage and aeration. Barley soils on the whole are heavier and other analyses show they may be much shallower. Fruit and hops

both require deep soils, and only seem to find their most favourable circumstances in a restricted class of soils: the fruit soils generally contain rather more sand and less silt than the hop soils. But the fruits differ among themselves; the best nursery stock is raised on soils of the potato class, where the conditions are for some unknown reason very favourable to fibrous root development; strawberries prefer the lighter and apples the heavier kinds of fruit soil. Even different varieties of the same plant show distinct preferences for one class of soil over another: the finest varieties of hops are found only on the typical hop soils, and have to be replaced by coarser varieties directly it is desired to grow hops on heavier soils. Preferences for certain soil conditions are also shown by varieties of the common crops, oats, barley, wheat, etc.; unfortunately these can only be discovered by direct field trials, and even then the results only hold so long as similar conditions prevail and may often be reversed in a different climate or season.

Still more subtle differences may be observed: one and the same variety of a crop will acquire one habit of growth on one soil and a different habit on another. Wheat growing under the best soil conditions will produce stiff straw and ears well set with corn, so that a crop of fifty or sixty bushels per acre may be raised without difficulty; on soil rather different in type, and especially under somewhat different climatic conditions, only thirty or forty bushels can be raised, because the ears are less thickly set and the straw is too weak to carry a heavier crop, becoming "laid" directly an attempt is made to increase production by increased manuring.[1] Whether some unknown nutrient is absent from these soils, or whether the adjustment of the air and water supply is wrong, is not known; but the limitation of yield arising from this unsuitability of soil conditions is one of the most serious problems of our time. Another instance may be given: in Romney Marsh pastures commonly occur carrying a vegetation of rye grass and white clover, with crested dog's-tail and agrostis, easily capable of fattening sheep in summer without any other food. All round these pastures are others, with *the same type of vegetation*, but the plants grow more slowly, produce more stem and less leaf, are less nutritious and *incapable of fattening sheep*. The soils are identical in mechanical analysis and in general water and temperature relationships, although certain differences have been detected (123). Again: grass grown on Lower Lias pastures in Somersetshire causes acute diarrhœa ("scouring") in cattle, whilst grass on adjoining alluvial

[1] Further illustrations are given by the author in *Science Progress*, 1910, v., 286.

pastures does not (105). Lastly: potatoes grown in the Dunbar district are remarkable for their quality, they will stand boiling and subsequent warming-up without going black. The same varieties of potatoes grown in the same way in the Fens blacken badly under the same treatment, and consequently command a much lower price in the market (8). Instances might be multiplied; enough have been given to show that the plant responds in a remarkable degree to variations in soil conditions. Our knowledge of these variations is fragmentary and wholly empirical, and would be much furthered by close and detailed study, jointly by a botanist and a chemist, of the factors causing differences in plant associations in two nearly similar habitats.

The agricultural treatment of loams, as already indicated, admits of considerable variety. The old plan was to apply a good dressing of dung every third or fourth year and a smaller intermediate dressing; clover was also grown every fourth year, and, on light loams, the root crop was eaten by animals on the land. At long intervals lime was applied and sometimes bones. The modern movement is towards specialisation, each man producing the crops he can best grow and managing them in the way he finds most profitable, but the system usually involves feeding a good deal of imported food to sheep and cattle, either on the land or in yards, and utilising the excretions as manure, buying nitrate of soda, sulphate of ammonia, and manufacturers' waste products (generally those derived from imported animal or vegetable products) to supply more nitrogen, and buying also imported phosphates and potassium salts. Thus the fertility of highly-farmed countries like England tends to increase at the expense of new countries that export large amounts of animal and vegetable produce. But the transfer is prodigiously wasteful; enormous losses arise in virgin countries through continuous cultivation (p. 81), and at this end in making dung (p. 89), and especially through our methods of sewage disposal. It seems inevitable that these losses must make themselves felt some day, unless the movement for the conservation of natural resources ever becomes a potent factor in international life.

Soil Fertility and Soil Exhaustion.

From the preceding paragraphs it is clear that fertility is not an absolute property of soils, but has meaning only in relation to particular plants. Plant requirements vary; a soil may be fertile for one plant and not for another; every soil might conceivably prove fertile for something. But in practice the agriculturist can only find use for a very limited number of plants; he, therefore, has to select those combining

the double features of saleability in his markets and suitability to his conditions of soil and climate. To a certain extent it is possible to bridge the gap between plant requirements and soil conditions: the former may be permanently altered by breeding if suitable plants cannot be found by selection, and the latter may be changed by such processes as draining, liming, etc. When all has been done that is economically possible there may still remain a divergency between the conditions ideal for the plant and those it finds in the soil; this divergency is the measure of the infertility of the soil for the crop.

The problem has to be simplified by restricting attention to the common agricultural crops and interpreting fertility to mean the capacity for producing heavy crops regardless of any subtle distinctions of quality. Three factors then come into play: an adequate supply of air and water to the roots, a sufficiently rapid production or solution of food material, and absence of harmful agencies. These have already been discussed in Chapters III. and V., where also it is shown that the three are not independent, but related to one another, inasmuch as they are all directly bound up with the nature of the compound particles, and, therefore, with the ultimate particles as revealed by mechanical analysis, and with the amounts of calcium carbonate and of organic matter.

We have seen that the compound particles can be altered considerably by human efforts, within limits fixed by the properties of the unalterable ultimate particles. In trying to improve a soil, therefore, four courses are open:—

1. The water supply may be increased by deepening the soil, *e.g.*, by breaking a "pan," by enriching the lower spit, or other device, while the air supply can be increased by drainage.

2. The compound particles may be built up by proper cultivation and the addition of organic matter (*e.g.*, dung, green manuring, etc.) and of calcium carbonate.

3. Sufficient calcium carbonate must be added for the needs of the crop and the micro-organisms—nothing but a field trial can determine what this is.

4. The food supply can be increased by the addition of fertilisers, the ploughing-in of green leguminous crops, feeding cake on the land, etc.

Conversely the "exhaustion" of soil is limited in our climate to the removal of organic matter, calcium carbonate, and some of the food (often the nitrogen compounds), and the destruction of the desirable compound particles; the ultimate particles, and all the possibilities they

stand for, remain untouched. A distinction is therefore made between the temporary fertility or "condition" within the cultivator's control, and the "inherent" fertility that depends on the unalterable ultimate particles. Of course the distinction is very indefinite and, in practice, wholly empirical, no proper methods of estimation having yet been worked out, but it is of importance in compensation and valuation cases.

Serious soil exhaustion did not arise under the old agricultural conditions where the people practically lived on the land and no great amount of material had to be sold away from the farm. Phosphate exhaustion was the most serious occurrence, and as the original supplies were not as a rule very great, it must have become acute by the end of the eighteenth century in England, for remarkable improvements were, and still are, effected all over the country by adding phosphates. Then began a process, which has gone on to an increasing extent ever since, of ransacking the whole world for phosphates; at first the search was for bones, even the old battlefields not being spared if we may believe some of the accounts that have come down; later on (in 1842) Henslow discovered large deposits of mineral phosphates to which more and more attention has been paid.

The crowding of the population into cities, and the enormous cheapening of transport rates, led during the nineteenth century to the adoption in new countries, particularly in North America, of what is perhaps the most wasteful method of farming known: continuous arable cultivation without periodical spells of leguminous and grass crops. The organic matter was rapidly oxidised away, leaching and erosion increased considerably when the cover of vegetation was removed, while the compound particles that had slowly been forming through the ages soon broke down. Nothing was returned to the soil, the grain and other portable products were sold and the straw burnt. The result has been a rate of exhaustion unparalleled in older countries, and wholly beyond the farmer's power to remedy, consequently he left the land and moved on. The excellent experimental studies of Hopkins (139) at the Illinois Experimental Station. of Whitson (307) at Wisconsin, and other American investigators, have shown that additions of lime, of phosphates and sometimes of potassium salts, with the introduction of rotations, including grass and leguminous crops, and proper cultivations will slowly bring about a very marked improvement.

CHAPTER VII.

SOIL ANALYSIS AND ITS INTERPRETATION.

When an agricultural chemist is asked to analyse a soil he is expected to give some information about the crops to which it is best suited, and the manures that must be applied; he has, therefore, a much more complex problem than the minerological or geological chemist who simply has to report on the actual constituents he finds. It has been shown in the last chapter that the vegetation relationships of soils are not determined solely by the nature of the soil, but also by its position, subsoil, climate, and other circumstances, so that it is manifestly impossible for the chemist to make a satisfactory report on a sample of soil on the basis of analytical data only. He cannot even give a complete account of the soil itself, since he has no method of estimating the compound particles on which the water and air supply, the temperature and the cultivation properties depend, but he can only get at the ultimate particles out of which they are built.

Soil analysis is, therefore, restricted to: (1) comparisons between soils, showing which are fundamentally identical and in what respects others differ; (2) the tracing of such correlations as exist between the chemical and physical properties of the soils of a given area and the crops and agricultural methods generally associated with them. In order to carry out either of these satisfactorily it is necessary to make a systematic soil survey, a task that is certainly laborious but by no means impossible, since each agricultural chemist usually confines his attention to a definite region—a county or so—and is not called upon to deal with outside soils.

In planning a soil survey it must be remembered that the basis of the whole work is empirical: the agricultural and vegetation characteristics have first to be ascertained by field trials, and then systematised and amplified by aid of the laboratory data. It is necessary to begin, therefore, by going over the whole region very carefully and dividing it up in areas within which similar agricultural or vegetation characteristics prevail. In general the areas differentiated in the geological drift maps will be found identical with the vegetation areas, especially

if the drift map is interpreted in the light of the *Memoirs of the Geological Survey*. But as agriculture is influenced by altitude and rainfall, the investigator must also use an ordinary contour map and a rainfall map which, unfortunately, he must construct for himself from data in *British Rainfall*. Within each vegetation area a number of soil samples must then be taken from points representing the area as closely as possible: situated, for example, on level regions or long gentle slopes, and not on made ground, steep slopes, or places of local disturbance, etc.

In seeking for typical places the investigator is likely to meet with a good deal of discouragement; farmers will tell him that half a dozen or more different kinds of soil occur on their particular farms, while the vegetation of a wild area may show considerable changes. But these differences often arise from differences in the compound particles and not in the ultimate particles; small variations in the amount of calcium carbonate or of organic matter, or differences in the water supply, or management, may considerably affect the ease of cultivation and the vegetation relationships and give the impression of a wholly different type of soil. So little does cropping, cultivation, etc., affect the ultimate particles that it is quite immaterial for the purpose of a soil survey whether the sample is taken from pasture land or arable land, but it is well to take a number of samples from both. With a little practice abnormal places are easily avoided. It is necessary to take a large number of samples not only to get at the type, but also to trace out the causes of the phenomena noted by the farmer, and to discover the main factors determining the cultivation and vegetation relationships of the soil. Very full inquiries must be made on the spot as to the agricultural value of the land, the crops and manures most suitable, its behaviour during drought and wet weather, and any special points to be observed during cultivation. Information is also wanted about the most troublesome weeds, the native vegetation, hedgerow and other timber, etc., and note must be taken of the position of the soil in regard to water supply, the nature of the strata down to the permanent water table, etc. The most reliable information is obtained only by properly conducted manurial trials.

It is usual to take the sample to a depth of 9 inches and a lower sample to a depth of 18 inches, but if any marked change occurs in the soil the sample should only be taken to the point where it sets in. The subsoil sample does not characterise the formation any better than the surface sample, but it affords a useful check and helps in detecting abnormalities.

The vegetation areas correspond with the geological formations only so long as the lithological characters remain constant. Some formations are very uniform, *e.g.* the Folkestone beds of the Lower Greensand, but, in general, certain changes are observed. Where the formation has been laid down in an estuary of no very great size, the coarser particles are deposited near the old shore and the finer particles farther out, so that a gradual change from finer to coarser soil is observed in travelling along the formation, necessitating a soil division into two or three vegetation areas; the Hythe beds of the Lower Greensand and the London clay afford illustrations. Considerable trouble often arises when the formation consists of a number of strata of sands and clays, and the outcrops are so narrow that no one type persists over any large area. The simplest method of procedure is to map out any uniform areas that possess sufficient agricultural importance, and then group the remaining less important soils simply into gravels, sands, loams, and clays. In dealing with drift soils, it is well first to map the uniform areas and then look out for lines of uniformity and make up regions within which the agricultural characteristics vary between a higher and a lower limit. The investigator must be guided by the importance of the region from the particular point of view in deciding how closely he is to map out the country.

Absolute uniformity cannot be expected over any considerable area, and even such uniformity as existed has often been upset by subsequent rearrangements of the soil which result in the original surface being covered up with a later deposit or being washed away, leaving the original subsoil to become the new soil. Such changes are readily detected by mechanical analysis of the surface and subsoils; examples are given in Table LII. At Merton the subsoil on the lower ground appears to have been the original surface soil because of its identity with the surface soil and its marked difference from the subsoil of the land higher up; it has been covered with a deposit identical with and presumably derived from the higher lying soil. The same thing has happened at Hamsey Green. At Woodchurch, however, it appears that the old surface of 69, now the subsoil, has been covered with rather a lighter soil; it is equally possible, however, in this particular case that 70 has lost its original surface soil, the present surface being the bared subsoil. This kind of variation is common on clay soils and often leads to differences in agricultural value that are fairly marked, but not sufficient to affect the type. Normally the subsoil contains more clay than the surface soil (as in 110, 69 and 70) and any deviation should be carefully investigated.

TABLE LII.—VARIATION IN SOIL DUE TO WASHING OR FLOODING.

Formation	London Clay.				Clay-with-Flints.				Weald.			
Locality	Merton, Surrey.				Hamsey Green, Surrey.				Woodchurch, Kent.			
	Lower Ground.		On the Hill.		Soil 109.		Soil 110, 200 yards away.		Soil 69.		Soil 70.	
	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.
Fine gravel	1·7	1·3	1·5	0·3	1·6	3·1	1·7	1·4	0·5	0·6	0·9	0·7
Coarse sand	18·4	23·6	16·9	8·4	9·5	6·7	5·3	7·1	2·5	1·9	1·1	1·1
Fine sand	12·7	11·3	12·4	12·7	22·3	28·0	28·7	25·1	14·7	13·0	9·3	9·0
Silt	16·6	18·0	16·6	13·4	25·4	22·5	26·3	17·6	24·2	27·8	25·9	18·8
Fine silt	11·1	11·4	10·1	9·8	9·9	12·6	10·2	9·5	23·7	23·3	24·4	26·5
Clay	24·6	24·9	26·7	41·7	16·0	16·4	16·4	28·3	20·1	28·9	28·6	37·8

The characterisation of soil types is sufficiently effected by mechanical analysis and determinations of calcium carbonate and organic matter. A representative set of soils should, however, be subjected to chemical analysis, the clay fractions being, if possible, broken up by ammonium fluoride and analysed completely. Soils about which precise information has been obtained by manurial and other trials should be very completely examined in order that they may serve as standards in the analysis of other soils from the same area.

The problem set by the farmer is wholly different. He does not want to know to what type his soil belongs, but how he must manure it, etc. If the analyst has an adequate knowledge of the soil type and the locality he can readily ascertain in what respects the soil differs from the type, and then, from the known results of manurial and other trials on that type, he can give the information wanted with a reasonable degree of probability; otherwise his report can only be a matter of guesswork. In short, the farmer's problem can be satisfactorily solved, and the manurial trials fully interpreted, only when a complete soil survey has been made.

The analyst must consider the soil from three points of view: (1) its physical properties, especially those relating to the ease of movement of the soil water; (2) its store of plant food, actual and potential; (3) the rate at which potential food can be converted into actual food.

The Interpretation of Mechanical Analyses.[1]

The properties of the various fractions have already been given in Chapter III., but some little practice is necessary before they can be used for the interpretation of an analysis. A few illustrations are therefore given from Hall and Russell's survey of Kent, Surrey, and Sussex (123): the data are set out in Table LIII.

The Chilworth soil contains so little clay and fine silt and so much coarse sand that it has very little power of retaining water. As it lies too high to obtain any seepage water from the neighbouring formations it is dependent on the immediate rainfall, and is therefore not in cultivation but has always been heath land. Owing to its bad constitution and its high situation it could not by any known method be made suitable for farming.

TABLE LIII.—MECHANICAL ANALYSES OF SOILS AND THEIR INTERPRETATIONS.

Formation	Folkestone Beds.		Thanet Beds.		Brick Earth.		London Clay.	Weald Clay.	Alluvium.	
Locality	Chilworth.	Shalford.	Goldstone.	Barton.	Ickham.	Oving.	Tolworth.	Shaddoxhurst.	Ewhurst.	
Gravel	1·2	2·5	0·2	0·2	0·3	0·9	0·4	0·2	0·7	0·1
Coarse sand	65·9	52·6	15·3	2·3	0·7	1·3	12·8	1·5	1·0	0·5
Fine sand	23·7	26·2	44·9	34·7	24·7	16·0	25·5	11·0	19·8	19·3
Silt	2·4	4·8	17·3	36·2	44·8	35·5	11·3	29·6	28·4	13·0
Fine silt	2·0	3·5	6·3	6·3	8·6	13·3	11·1	26·8	12·1	20·0
Clay	0·9	3·8	8·9	11·5	14·7	15·9	23·7	22·1	19·7	26·9
Calcium carbonate	nil	0·3	0·08	0·18	0·40	0·75	2·0	0·16	0·05	0·28
Loss on ignition	2·6	3·3	3·1	4·3	4·6	6·5	5·6	9·8	10·2	11·3

The Shalford soil lies lower down and has a better water-supply, less coarse sand and more clay and fine silt. But its water-holding capacity and its retentive power for manures are still very low; artificial manures are of much less value than organic manures, and the best treatment of the land is to grow green crops and fold them off to sheep. It is better suited to special purposes like the production of malting barley or market-garden crops than to ordinary mixed farming.

The Goldstone soil contains more clay and fine silt, and has therefore better power of retaining water and manures, and is more productive and more generally useful. But as the coarse sand exceeds the clay in amount it is still distinctly light; it responds better to organic than to artificial manures and suffers rather in droughty weather in

[1] See Appendix for Methods of Analysis.

spite of lying not far above the marshes. It contains 45 per cent. of fine sand and therefore tends to cake on the surface after rain and to form steely lumps if worked when wet. Under proper management, however, it produces good crops and is equally suited for ordinary arable and for fruit or potato cultivation.

The next three soils may be taken as illustrations of the very best loams in the three countries. Silt forms the largest fraction and therefore the soils possess sufficient, but not too great, a power of retaining water. The fine silt is always lower than the clay; the latter varies between 12 and 16 per cent., a very satisfactory amount where the rainfall is not too high. As there is a considerable amount of fine sand and no excess of fine silt and clay, the absence of coarse sand is no disadvantage.

The Tolworth soil is highly productive arable land but almost too heavy for profitable cultivation; only by dressings of dung (fortunately obtainable cheaply from town) can it be kept workable. It contains rather too much clay and would no doubt have gone down to grass had there not been so much coarse sand present.

The Shaddoxhurst soil is bad. It contains much clay and still more fine silt, consequently its texture is not improved as much as might be expected by liming. There is practically no coarse sand and not much fine sand to keep the soil open, it has always and deservedly been in bad repute. It is best as pasture land, and, after drainage and treatment with basic slag, it may be made useful but never first rate.

The Ewhurst soils are both in pasture, being too heavy for arable cultivation on account of their high clay and low coarse sand content. The first has the better constitution; silt is the predominant feature, the clay is not too high, nor is the fine silt. It has all the characteristics of a good, if heavy, soil, and is indeed known to be an excellent bullock pasture. The second is not so good; it contains too much clay and fine silt, and too little silt and coarse sand. It has no great agricultural value.

Factors Modifying the Interpretation of a Mechanical Analysis.

The Amount of Organic Matter.—Organic matter at the proper stage of decomposition has the effect of binding a loose soil and lightening a heavy one; thus it reduces the difference between a light sand and a heavy clay, bringing them both closer to the loams. When 10 to 15 per cent. of organic matter is present it so impresses its properties on the soil that the mechanical analysis loses much of its significance, and all the analyst can do is to point out what the soil would become

if by persistence in certain methods of management the organic matter were reduced below a certain point.

It is, however, essential that the organic matter should be properly decomposed. Barren sandy wastes not infrequently contain 5 to 10 or even 15 per cent. of organic matter, but much of it is simply dried bracken or other vegetation that has not broken down and has no value, but rather the reverse, in improving the physical conditions. If the drainage is bad a good deal of peat may form; further, the water fills up the soil, making its condition bad whatever its composition may be.

The Amount of Calcium Carbonate.—In interpreting a mechanical analysis it must be remembered, as shown on page 61, that 1 or 2 per cent. of calcium carbonate may greatly modify the clay properties and give a considerable degree of friability to a soil which otherwise would be very intractable. When the percentage rises to much higher amounts the soil becomes very chalky and the mechanical analysis loses its meaning, just as when much organic matter is present.

Water-supply and the Interpretation of Mechanical Analysis.

It has already been pointed out that a mechanical analysis can be interpreted and discussed with any degree of completeness only in terms of the water-supply; the rainfall, the coolness of the climate, the presence of moving underground water, and the nature of the subsoil all have to be taken into account.

Effect of the Rainfall.—The effect of a high rainfall is to bring into prominence the "sticky" properties of the fine fractions, and to put into the background their water-holding capacity. Thus a light soil under a high rainfall behaves like a heavier soil under a low rainfall; it is as well supplied with water and on the whole behaves in the same kind of way on cultivation. For example, the Stedham soil (Table LIV.) is rather lighter than the Swanley soil, and yet in virtue of its extra rainfall is more useful for farming purposes; indeed the Swanley soil is essentially a market-garden soil, requiring large dressings of dung for successful cultivation. The North Chapel soil is physically as good as the East Farleigh soil but agriculturally much inferior; owing to the higher rainfall it becomes somewhat too sticky to cultivate profitably and so is in rather poor grass; the East Farleigh soil, on the other hand, is from a highly fertile hop garden.

Coolness of Climate.—Soils containing so much coarse sand or fine sand that they would scorch or burn in a dry warm district may prove very suitable for cultivation in a cooler district where evaporation is lessened. Potato soils afford some good illustrations; potatoes require a

light soil, but it must be cool and moist. The Nutfield soil (Table LIV.) fulfils these conditions; it is on a slope facing northwards not very far above a stream, and, therefore, does not quickly dry out, hence it is very good for main crop potatoes. The Tolworth soil, on the other hand, although similar in composition, is so placed that it quickly dries and is of much less value. Some of the potato soils of Dunbar, analysed by S. F. Ashby (8), have all the appearance of soils readily drying out, but in their cool climate this property does not show itself to an injurious extent.

TABLE LIV.—WATER-SUPPLY AND INTERPRETATION OF MECHANICAL ANALYSIS.

	Swanley.	Stedham.	North Chapel.	East Farleigh.	Tolworth.	Nutfield.	Dunbar.	
Fine gravel	1·2	1·4	0·9	2·3	0·6	2·9	3·0	1·0
Coarse sand	10·2	9·3	11·4	9·5	37·8	46·6	33·8	23·7
Fine sand	58·6	68·5	43·2	30·6	33·1	22·9	28·0	38·2
Silt	13·3	3·6	13·0	19·7	7·7	3·5	5·5	6·8
Fine silt	5·1	5·6	10·2	11·1	4·7	8·8	10·8	11·8
Clay	5·5	5·5	10·9	13·3	7·6	6·9	6·6	9·5
Loss on ignition	2·9	3·4	5·1	5·6	3·6	3·6	6·9	6·2
Calcium carbonate	·02	·03	·80	1·0	·27	·21	·15	·31
Rainfall in inches (approximate)	24	33	30	24	28	27·5	25	25

Effect of Underground Water.—When the underground water is near the surface, but sufficiently far below to allow of proper root development, the most important property of the soil becomes its power of lifting the water by surface action up to the roots. The silt and sands are in such cases the useful constituents, the clay and fine silt being less necessary. The Weybridge soil (Table LV.), at about 3 feet below its surface, has a current of underground water which is brought to the roots by the fine and coarse sand. It therefore grows excellent wheat crops. The Bagshot sands, however, although similar in physical type, have in general no such water-supplies and are sterile because they lack the clay which, in their circumstances, could alone confer an adequate power of holding water from one shower to the next.

TABLE LV.—UNDERGROUND WATER AND MECHANICAL ANALYSIS.

	Weybridge.	Bagshot Beds.	Shalford.	Lydd.
Fine gravel	1·3	·1 to ·6	2·5	0·1
Coarse sand	38·4	20 to 30	52·6	0·9
Fine sand	39·9	45 to 65	26·2	66·7
Silt	5·6	5 to 10	4·8	7·2
Fine silt	5·1	5 to 10	3·5	11·4
Clay	3·8	3 to 7	3·8	3·9

The Shalford soil is a light sand with too little power of retaining water for pastures to last through a hot summer, consequently the grass-land, except near the brooks, is parched and scorched. The Lydd soil is certainly somewhat finer grained, but not so very different that one would expect to find it much better for pasture purposes, yet it produces one of the best pastures in Romney Marsh, not only carrying but fattening sheep throughout the summer. It has, however, a constant supply of water 3 or 4 feet below the surface, while at Shalford the water level is much lower down.

This underground flow is one of the factors concerned in the proverbial fertility of valleys. Soils lying towards the bottom of a long slope receive not only the rainfall but also the water steadily drifting downwards to the stream or marsh at the bottom, and this advantage is further enhanced by the gradual transport of soil down the slope which increases the depth through which the plant roots can range.

Effect of the Subsoil.—In general the subsoil is rather heavier in type than the surface soil, especially in the case of clays; examples are given in Table LVI. The rare exceptions to this rule may arise through periodical flooding with water containing much clay in suspension, or through the occurrence of a bed of sand just below the surface.

Two cases described on page 126 may be illustrated here. The bad effect of a layer of impermeable material near the surface is shown by the Loddington soil (Table LVI.), typical of an area near Maidstone (Cox Heath), much of which was waste land. Its sterility was due to no

TABLE LVI.—NATURE OF THE SUBSOIL.

	Loddington.		Harting.		Dicker.		Shopwyke.		Wye.	
	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.
Fine gravel	3·5	2·6	0·6	0·2	1·0	0·6	0·6	0·1	1·0	0·2
Coarse sand	10·2	9·8	3·3	3·2	2·0	1·1	0·8	0·4	3·0	1·9
Fine sand	33·5	30·2	31·6	33·9	26·6	23·2	25·0	21·9	27·2	25·3
Silt	14·6	17·5	17·3	21·3	23·0	15·1	27·3	38·0	40·0	41·4
Fine silt	14·9	15·5	14·5	13·4	17·8	21·9	16·4	15·2	8·9	9·6
Clay	12·2	15·3	12·3	16·0	17·9	25·7	11·1	15·7	11·2	14·5

fault in the soil, which is obviously of excellent type, but to a thin layer of rock lying near the surface. When this was removed a very good soil was obtained. The Harting soil lies on the Upper Greensand in West Sussex; the rock comes close to the surface, restricting both the

root range of the plant and the water supply where it lies horizontally, but proving much less harmful where it dips at any considerable angle. The soil itself is good although it has rather too much fine silt, and it becomes very productive when the effect of the rock is counteracted. The Dicker soil, while not of the best type as its fine silt is too high, is far from being hopeless, but it unfortunately lies on a deep bed of stiff clay which keeps it wet in winter and parched in summer. It is therefore very poor, and even with the best management never gives great results.

The second case, over-drainage, is illustrated by the Shopwyke soil in the same table. It is a fair soil, containing too much fine silt to be in the first rank, but it is spoiled by lying on a deep bed of gravel only nine inches or a foot below the surface—the subsoil sample could only be taken in one or two instances. Consequently it dries out badly in summer and does not repay much expenditure in the way of manures.

The Wye soil is given as an instance of the normal case where a soil becomes rather heavier in its lower depths, with the result that the movement of water is somewhat impeded without being stopped. Thus the subsoil furnishes a reserve of water for the surface, yet even in wet weather it does not hold up too much water and in dry weather does not constitute too great a barrier against the upward capillary movement. The Wye soil contrasts with the Dicker soil, the usual case in a clay, where the subsoil contains much more true clay than the surface.

Chemical Analysis of Soils.[1]

Recourse is had to chemical analysis to discover the amounts of potential and actual plant food in the soil, and the rate at which potential food is likely to become available. But as the problem is vague, so the methods are empirical and the interpretation of the results often very difficult.

Organic Matter.—The analyst should note whether the organic matter is fairly well decomposed, or whether it still shows definite plant structure, also whether or not it is acid to litmus paper. He can then interpret his observations as shown on pages 69, 70 and 121.

Nitrogen.—Unlike the other soil constituents nitrogen and carbonates are determined absolutely. The amount of nitrogen is closely related to the loss on ignition, of which in a large proportion of cases it is about 3 per cent. As a guide to fertility it is therefore subject to the same limitations; a high nitrogen content may be associated either

[1] See Appendix for methods of analysis.

with a rich soil containing abundance of valuable non-acid organic matter, or with a soil where the conditions are so unfavourable that organic debris does not decompose, or only forms accumulations of peat. On the other hand some of the best loams, where the conditions are most favourable to rapid decomposition and nitrification, contain but little nitrogen. A few typical examples are given in Table LVII.

TABLE LVII.—NITROGEN AND LOSS ON IGNITION.

	Fertile Arable Soils.				Poor Arable Soils.				Barren Wastes.		
Loss on ignition	4·65	6·58	3·70	4·65	4·13	6·23	3·60	5·14	5·94	7·00	5·81
Nitrogen	·120	·220	·133	·141	·128	·143	·182	·152	·130	·195	·167
Loss on ignition in subsoil	3·00	4·94	2·81	3·29	3·74	5·50	2·58	4·14	—	—	2·70
Nitrogen in subsoil	·078	·139	·081	·097	·112	·104	·061	·096	—	—	·058

Soils containing much calcium carbonate are as a rule rich in nitrogen, partly no doubt because of the rather high nitrogen content of the rock and partly also because they are folded, green manured, cropped with leguminous plants like sainfoin, lucerne, etc., all of which tend to increase the nitrogen supply. The nitrogen in some chalk soils is as follows :—

Nitrogen in surface soil	·25	·194	·331	·258	·249	·419
,, subsoil	·128	·130	·162	·192	·196	·180
Calcium carbonate in surface soil	18·1	3·70	49·7	66·0	65·6	44·0
Calcium carbonate in subsoil	11·37	14·9	61·3	55·2	54·8	71·6

All are arable soils, excepting the last, which is open downland.

Carbonates.—The analyst is often asked whether or not a particular soil contains sufficient calcium carbonate, and in endeavouring to answer this question he must bear in mind the twofold function of this substance, to prevent "sourness" (p. 62), and to flocculate the clay. Where only a small amount of clay—say 8 per cent. or less—is present the flocculating action is less needed and a smaller amount of calcium carbonate suffices. The Stedham soil (Table LIV.) is an example; it is near the bottom of a slope along which water containing calcium bicarbonate in solution is drifting, and therefore shows no tendency to become sour. The 0·03 per cent. of calcium carbonate present, hopelessly inadequate as it appears, suffices for its needs and no increase in crop is obtained by applying lime. The Lydd soil (Table LV.) contains only ·02 per cent., but is also well supplied with calcareous water from below and shows no sign of sourness. Similar soils that have not

this advantage of position stand in great need of lime even when 0·1 per cent. is present. As the amount of clay increases, the need for lime becomes greater because flocculation is now wanted; soils with 20 per cent. or more of clay need two or three times as much lime as sandy soils. It is impossible to fix limits that shall hold universally. Before an analyst recommends lime or chalk on a sandy soil he should satisfy himself that acid indicators like finger-and-toe, spurry, etc., are present, and before he states that lime is not necessary on a clay he should be quite sure that further additions would have no beneficial flocculating effect. The following soils were known to respond to lime:—

Sandy Soils.			Loams and Clays.		
No. of Soil.[1]	Percentage of Clay.	Percentage of Calcium Carbonate.	No. of Soil.[1]	Percentage of Clay.	Percentage of Calcium Carbonate.
126	7·8	·04	207	11·1	·02
675	8·9	·08	119	10·4	·03
193	6·0	·18	118	11·5	·18
189	3·8	·35	152	12·2	·26
			215	13·0	·45
			127	13·3	1·00

Alumina.—In general the alumina is approximately equal in amount to one-third of the clay fraction, indicating that the acid treatment breaks down some definite group of silicates associated mainly with the clay fraction in the soil. The following examples may be quoted:—

Formation.	Bagshot Sands.			London Clay.		Thanet Beds.		Sandgate Beds.	Folkestone Beds.	Weald Clay.
Percentage of clay in soil .	3·6	4·9	7·1	36·8	21·3	11·5	7·1	15·3	6·9	33·8
Percentage of Al_2O_3 in soil	·92	1·43	1·94	11·75	6·78	3·46	2·66	5·14	1·99	10·45
Ratio $\frac{Al_2O_3}{clay}$	·25	·29	·27	·31	·31	·31	·37	·33	·28	·31

Exceptions to the rule occur when much fine silt is present, the alumina then being markedly less than one-third of the clay:—

Formation.	Weald Clay.			Lower Wealden Beds.			Upper Greensand.		Gault.
Percentage of fine silt in soil .	27·4	35·8	25·9	15·8	21·5	14·3	15·9	14·5	14·0
" clay in soil .	21·5	22·1	19·4	5·4	12·5	9·7	13·1	12·3	11·8
" Al_2O_3 . .	5·02	5·42	5·68	·17	1·66	2·38	2·48	2·39	5·11
Ratio $\frac{Al_2O_3}{clay}$	·23	·25	·29	·03	·13	·24	·18	·19	·43

[1] The numbers are those used in *Soils and Agriculture of Kent, Surrey, and Sussex* (Hall and Russell).

Iron Oxide.—The iron oxide is present in quantities comparable with those of alumina, but no close relationship is observable, nor does the amount of iron oxide afford any indication of the fertility of the soil. Light soils, good or bad, contain about 1 to 2·5 per cent., good loams, and poor clays contain 3·5 to 5 per cent. Larger amounts of iron oxide are not common. Soils containing ferrous compounds are generally of no great fertility.

Lime and Magnesia.—About ·1 to ·5 per cent. of magnesia is found in the soils we have examined, and in general the $\frac{\text{lime}}{\text{magnesia}}$ ratio falls between 1 and 3, but ratios of 4 and 5 are not uncommon, while on chalk soils they may rise very high. No connection could be traced between the $\frac{\text{lime}}{\text{magnesia}}$ ratio and the productiveness of the soil, indeed Table LVIII. shows that very good and very poor soils may have practically identical ratios.

TABLE LVIII.—$\frac{\text{LIME}}{\text{MAGNESIA}}$ RATIO IN VARIOUS SOILS.

Barren Wastes.				Poor Cultivated Soils.				Fertile Soils.			
No. of Soil.	CaO.	MgO.	Ratio $\frac{CaO}{MgO}$	No. of Soils.	CaO.	MgO.	Ratio $\frac{CaO}{MgO}$	No. of Soil.	CaO.	MgO.	Ratio $\frac{CaO}{MgO}$
170	·05	·06	1·0	45	·43	·23	1·9	183	·56	·40	1·4
192	·13	·08	1·6	242	·30	·13	2·3	222	·46	·28	1·6
168	·21	·13	1·6	106	·48	·21	2·3	152	1·02	·41	2·5
50	·15	·08	1·9	255	·89	·27	3·4	122	·60	·22	2·7
197	·21	·08	2·6	196	·43	·12	3·6	211	1·79	·40	4·5
91	·08	·03	2·7	287	1·19	·29	4·0	72	1·94	·42	4·6
241	·22	·07	3·1					127	2·14	·40	5·4
13	·58	·14	4·1								

Potash.—The amount of potash is closely associated with that of alumina, being commonly about one-tenth; it is, therefore, about one-thirtieth of the clay. Some examples are:—

No. of Soil.	Percentage of Al_2O_3.	Percentage of K_2O.	Ratio $\frac{K_2O}{Al_2O_3}$.	Percentage of Clay.	Ratio $\frac{K_2O}{Clay}$.
112	4·07	·45	·11	13·1	·034
120	2·84	·31	·11	10·4	·029
100	3·83	·40	·10	11·2	·035
133	3·67	·44	·12	11·7	·037
103	3·66	·30	·08	11·9	·025
161	7·97	1·08	·14	27·7	·039
67	11·75	1·44	·12	36·8	·039
118	3·46	·404	·12	11·5	·035
79	5·14	·40	·08	15·3	·026
43	10·45	·76	·07	33·8	·022
147	7·88	·96	·12	22·5	·043

The "available" potash[1] shows no kind of regularity, but varies between 5 and 50 per cent. of the quantity extracted by strong acids. In deciding whether or not sufficient is present, attention must be paid to the soil, the crop and the rainfall. Thin chalky soils, sandy soils and soils rich in organic matter are peculiarly responsive to potassic manures, whilst clay soils generally are not. Carbohydrate-making crops, like sugar beets, mangolds and potatoes also invariably want more potash than they find in the soil or in dung. Potassic manures also tend to prolong the life of the plant, and, therefore, to increase the yield in dry districts where the conditions all tend to early stoppage of growth. Illustrations are afforded in Table LIX. where soils in dry districts, known to respond profitably to potassic manures, are compared with soils in places of much higher rainfall where potassic manures do not prove profitable.

TABLE LIX.—"AVAILABLE" POTASH IN SOILS OF KNOWN BEHAVIOUR TOWARDS POTASSIC MANURES.

	Soils Responding to Potassic Manures.				Soils not Responding to Potassic Manures.			
	East Kent.		Surrey.	Sussex.	West Sussex.			Kent.
	Newington.	Barton.	Redhill.	Patching.	Oving.	Rogate.	Stedham.	Yelding.
Available K_2O	·013	·015	·010	·007	·014	·024	·010	·044
K_2O extracted by conc. HCl	·200	·404	·181	·260	·43	·18	·14	·59
Clay	6·0	11·5	7·8	25·5	15·9	6·7	5·5	9·1
Rainfall	22·5	23	27·7	28·6	28	33	33	24

All are arable soils. The chalk pastures on the South Downs usually contain less than ·01 per cent. of available potash (*e.g.* the Patching soil), and they respond to potassic manures. It will be observed that ·015 per cent. is insufficient in East Kent where the rainfall is 23 inches, whilst ·010 per cent. suffices in West Sussex under 10 inches higher rainfall and generally better water-supply in the soil.

Phosphoric Acid.—Generally speaking, the largest amount of phosphoric acid is found in chalk soils, ·2 to ·25 per cent. being present; about ·15 to ·2 per cent. is found in good loams, sandy loams contain about ·1 per cent., while poor clay pastures and poor sands contain still less. Little if any direct connection can be traced between the phosphoric acid and the productiveness; in general it tends to increase as

[1] *i.e.*, extracted by 1 per cent. citric acid.

the clay, fine silt, and silt increase—the poor clay pastures form a readily explained exception—but it does not appear to be closely associated with any one fraction like the potash. The amounts of "available" phosphoric acid vary enormously; Kentish hop gardens commonly contain from ·05 to ·18 per cent.; well farmed arable soils contain some ·015 per cent., while in poor worn-out pastures the quantity may sink as low as ·002 per cent. In most cases these quantities are insufficient for some of the crops grown, especially where high quality or feeding value is aimed at; hop growers regularly, and, they maintain, profitably, apply phosphates to gardens already containing ·05 per cent. of available phosphoric acid, whilst arable farmers use them for swedes when ·015 per cent., or sometimes even more, is present. The exceptions to this rule are the light soils sufficiently provided with moisture and a forward climate; on these the need for phosphates appears to be less. But in all cases where much purchased food is fed on the land phosphates appear to be of advantage to the succeeding crop.

Rainfall does not appear to have so marked an effect in controlling the need for phosphates as it has for potassic manures. The explanation is to be found in the fact that phosphates are useful both in dry and in moist situations: they tend to promote root development, an obvious advantage in a dry soil where the plant will fail unless the roots strike into the deeper, moister layers; they also stimulate the vital processes going on at the end of the season and are thus valuable in wet, cold districts. But rainfall and water-supply are important factors in determining the choice of phosphates; basic slag proves less useful than superphosphates on dry soils, and at least as useful on moister soils or under higher rainfall. The amount of chalk in the soil is not the determining factor, but the moistness; if, as often happens, a chalky soil is dry, superphosphate will prove the more useful; where the soil is moister, basic slag is as good, and of course cheaper.

The Relative Advantages of Mechanical and Chemical Analysis.

The fundamental distinction between mechanical and chemical analysis is that the former deals with the whole of the soil, which it sorts out into fractions of varying sizes, while the latter only deals with the part that is readily dissolved by acids. Mechanical analysis therefore gives a complete picture while chemical analysis does not; it is in consequence eminently suited for the purpose of a soil survey, the chief object of which is to classify and describe the soils. Further, it enables

the investigator to explain with some degree of completeness the observed water relationships of the soil when sufficient is known about the water supply, and also to account for many of the peculiarities observed in cultivation. It enables him to say, as far as can be said on our present knowledge, whether any observed defects are due to defects in the soil or its situation, or to the system of management that has been adopted. As it cannot be interpreted fully without a knowledge of the amounts of organic matter and calcium carbonate present these two quantities must be determined in every sample.

We have seen that there is a close correlation between the potash, the alumina and the clay. For purposes of a survey it seems superfluous to determine these two bases in every sample taken. The iron oxide shows a general but by no means so close a correlation with the others; but no connection could be traced between iron oxide and fertility in the soils examined by the author, the iron oxide being almost always less than 5 per cent. in amount. Nor did it appear that the ratio of lime to magnesia in these soils was significant. The nitrogen is closely correlated with the organic matter, *i.e.* the loss on ignition. The total phosphoric acid does not show very great variations in the different soils, but the available phosphoric acid, like the available potash, varies greatly with the management of the soil. Thus the figures obtained by chemical analysis, apart from the loss on ignition and the calcium carbonate, fall into two groups: the nitrogen, potash, and alumina, which are so closely correlated with quantities already determined in the mechanical analysis that their separate determination is almost superfluous; and the iron oxide, magnesia, lime, etc., which do not give sufficiently useful indications to be worth determining in every case. Since chemical analysis fails to characterise the soil with sufficient completeness Hall and Russell recommend that for purposes of a survey a large number of soils should be submitted to mechanical analysis, including the determination of organic matter and of calcium carbonate, and then a carefully chosen representative set should be analysed chemically. They agree with Whitney that mechanical analysis should form the basis of the survey, because it alone takes account of those physical functions—the regulation of the water supply and therefore of the temperature, of the air supply, ease of cultivation, etc.—that play so large a part in determining the value of a soil.

But, on the other hand, mechanical analysis is restricted in its application and breaks down altogether on chalk soils, acid humus or peat soils, and neutral humus soils, while it gives useful indications only on the mineral soils, *i.e.* sands, loams and clays. Agricultural soils belong

so largely to this group that the method is really applicable in by far the great majority of cases.

Among the mineral soils there are indications of chemical groups cutting across the mechanical classification, but it is not easy to trace them because so much of every soil is silica. When, however, the clays are separated out and subjected to hydrofluoric acid treatment or fusion with alkalis and then analysed, they are seen to fall into two or more types as shown in Table XXIV. (p. 53 . Further evidence of dissimilarity among the clays is obtained by a study of the results of the acid extraction of the soil; in general the alumina is about one-third of the clay in amount and the potash is roughly one-tenth of the alumina; in exceptional cases, however, and usually where the abnormal clay occurs, very different relationships obtain. It will be necessary to accumulate many more analyses of clays before we shall have the material for chemical classifications.

APPENDIX.

THE METHODS OF SOIL ANALYSIS.

How to Take the Sample of Soil.—Owing to the variation in composition of the soil at different depths it is particularly necessary that the sample should always be taken to the same depth and with a tool making a clean vertical cut. Samples taken with a spade are of very doubtful value and do not justify any lengthy examination. The simplest tool is shown in Fig. 7 and consists of a steel tube 2 in. in diameter and 12 in. long, with a ⅜ in. slit cut along its length and all its edges sharpened. The tube is fixed on to a vertical steel rod, bent at the end to a ring 2 in. in diameter, through which a stout wooden handle passes. A mark is made 9 in. from the bottom so that the boring process can be stopped as soon as this depth is reached. On withdrawing the tool the core of soil is removed by a pointed iron rod. Five or six samples should be taken along lines crossing the field so as to get as representative a sample as possible; the whole bulk must then be sent to the laboratory. Samples should not be taken from freshly ploughed or recently manured land.

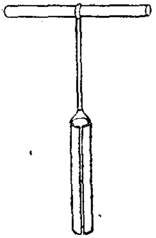

Fig. 7.—Tool for taking Soil Samples.

The Analysis.—On arrival at the laboratory the soil is spread out to dry, and is then pounded up with a wooden pestle and passed through a 3 mm. sieve. The stones that do not pass through, and the fine earth that does, are separately weighed, and the proportion of stones to 100 of fine earth is calculated. Subsequent analytical operations are made on the fine earth.

Moisture.—Four or five grams of the soil are dried at 100° C. till there is no further change in weight.

Organic Matter.—No accurate method of estimation has yet been devised. It is usual to ignite at low redness the sample dried as above. The loss includes organic matter, water not given off at 100° C., and carbon dioxide from the carbonates; allowance may be made for the latter, but not for the combined water. The carbon is sometimes determined either by the ordinary combustion or by some wet combustion method. Methods have also been described for determining "humus," but they have not come into general use. For ordinary purposes it is sufficient to determine the loss on ignition, and to call this organic matter.

Total Nitrogen.—Kjeldahl's method is almost invariably adopted. About 25-30 grams of soil are ground up finely in an iron mortar; 10-15 grams are then heated in a Kjeldahl flask with 20-25 c.c. of strong sulphuric acid for ¾ hour; then 5 grams of potassium sulphate are added, and shortly after a crystal of copper sulphate. The heating is continued till all the black colour has gone. Then cool and dilute the mixture, transfer the fluid part to a distillation flask, but leave as much as possible of the sand behind, wash well to remove all the adhering liquid. Add saturated soda solution till the liquid is strongly alkaline, distil, and collect the ammonia in standard acid.

Nitrates must be determined in a sample taken direct from the field and dried without any delay at 55° C.; 200-500 grams of the dried soil are pressed firmly on to a Buchner funnel fitted to a filter flask, and distilled water is poured on. The first 300 c.c. of water passing contains practically all the nitrates, but it is safer to wash more fully. The solution is concentrated in presence of a little magnesia, acidified with acetic acid, and reduced by a zinc-copper couple at 25° C. for 30 hours. The ammonia formed is estimated in the usual way.

Ammonia is estimated by distilling with magnesia and water under reduced pressure (241).

Carbonates are determined by treating a weighed quantity of the soil with dilute sulphuric acid and estimating the carbon dioxide evolved. Large quantities can be determined rapidly and with sufficient accuracy by the Scheibler apparatus, but much better results are obtained by absorbing the CO_2 in potash and determining the amount by titration. The details have been worked out by Amos.[1] Great care is needed when only small quantities are present; the treatment with acid must be effected at as low a temperature as possible to avoid decomposition of organic matter. Small quantities can also be determined by Hall and Russell's method.[2]

Mineral Substances.—Complete analysis of a soil after the silicates have been decomposed and the silica volatilised by treatment with hydrofluoric acid is only rarely attempted. The British method, adopted by the Agricultural Education Association, is thus described by Hall: "20 grams of the powdered soil are placed in a flask of Jena glass, covered with about 70 c.c. of strong hydrochloric acid, and boiled for a short time over a naked flame to bring it to constant strength. The acid will now contain about 20·2 per cent. of pure hydrogen chloride. The flask is loosely stoppered, placed on the water bath, and the contents allowed to digest for about forty-eight hours. The solution is then cooled, diluted, and filtered. The washed residue is dried and weighed as the material insoluble in acids. The solution is made up to 250 c.c., and aliquot portions are taken for the various determinations. The analytical operations are carried out in the usual manner, but special care must be taken to free the solution from silica or organic matter" (*The Soil*). As a rule only potash and phosphoric acid are determined, but where other bases are wanted they are estimated in the usual way.

[1] *Journ. Agric. Sci.*, 1905, i., 322-26. [2] *Journ. Chem. Soc.*, 1902, lxxxi., 81-85.

Potash.—50-100 c.c. of the solution are evaporated to dryness aft addition of 0·5 gram of pure $CaCO_3$ if the original soil did not effervesc when HCl was added. Two courses are then open :—

(*a*) The residue is *gently* ignited over a Bunsen burner till it is complete charred, it is then taken up with water several times till all the potassiu chloride is dissolved (Neubauer's method[1] (212)). To the clear filtrate 5 c. of platinum chloride (containing ·005 gram Pt per c.c.) are added and th mixture slowly concentrated on the water bath to a very small bulk. Th potassium platino-chloride is filtered off in a Gooch crucible, washed wit 80 per cent. alcohol, dried and weighed.

or (*b*) Add 10 c.c. of 5 per cent. baryta solution, evaporate to dryness ignite and take up with water as in (*a*), add 2·5 c.c. perchloric acid (sp. gr. 1·12) concentrate till dense fumes are given off, allow to cool, add 20 c.c. 95 per cent alcohol and stir. Decant off the clear alcohol, add 40 c.c. alcohol containin 0·2 per cent. perchloric acid, transfer to a tared filter paper, wash with 50-10 c.c. of 95 per cent. alcohol till the runnings are no longer acid, dry at 100° and weigh as $KClO_4$.

Phosphoric Acid.—The charred residue from which the potassium chloride has been removed is now extracted with hot dilute H_2SO_4, the filtrate is neutralised with ammonia, treated with 25 c.c. HNO_3 and 2c c.c. 0·9 sp. gr. ammonia. Warm to 55° C., add 35 c.c. ammonium molybdate, allow to stand for a short time, filter. Wash with 1 per cent. $NaNO_3$ till the washings are neutral, transfer the precipitate and filter paper to the beaker used for the precipitation, and add a known volume of standard alkali so that the precipitate completely dissolves. Measure the excess by titration, using phenolphthalein as indicator. If 323·7 c.c. of normal acid or alkali be diluted to 1 litre then 1 c.c. = ·001 gram P_2O_5.[2]

Available Potash and Phosphoric Acid.—Dyer's directions are as follows : 200 grams dry soil are placed in a Winchester quart bottle with 2 litres of distilled water in which are dissolved 20 grams of pure citric acid. The soil is allowed to remain in contact with the solution at ordinary temperatures for seven days, and is shaken a number of times each day. The solution is then filtered, and 500 c.c. taken for each determination ; this is evaporated to dryness, and gently incinerated at a low temperature. The residue is dissolved in hydrochloric acid, evaporated to dryness, redissolved, and filtered ; in the filtrate the potash is determined. For the phosphoric acid determination the last solution is made, as before, with nitric acid.

Mechanical Analysis.—The object is to obtain information about the size of the ultimate particles of which the soil is composed ; the compound particles are therefore broken down by treatment with hydrochloric acid, and after with ammonia. Direct measurement of the ultimate particles is found to be impracticable ; indirect methods have to be adopted, depending on the

[1] The older method due to Tatlock is still sometimes used. It is described by Dyer (91).

[2] This volumetric method is described in *Bull.* 46 (revised) *United States Division of Chemistry* (Washington, 1898). The older method is described by Dyer (91).

time taken to fall through a column of water of given height. When a body falls through a vacuum the time taken is independent of its size or weight, but if air or any other fluid is present the case becomes more complicated and the proper mathematical relationship has been found by Stokes to be $v = \frac{2ga^2(\sigma - \rho)}{9\eta}$, where v = velocity of the falling particle, σ its density, a its radius (assuming it to be a sphere), and ρ the density and η the coefficient of viscosity of the medium (*Trans. Camb. Phil. Soc.*, 1851, vol. ix., p. 8).

The numerical values at 16° C. are: $g = 981$, $\sigma = 2\cdot5$, $\rho = 1$, $\eta = \cdot011$, and the equation therefore reduces to $v = a^2 \times 29430$, or $a = \frac{\sqrt{v}}{171}$ cm.

The calculated and observed values are found to agree fairly well, differences being due to the fact that the particles are not true spheres, and to the existence of convection currents produced by changes of temperature.

The method adopted by the Agricultural Education Association (see *Journ. Agric. Science*, 1906, i., 470) is as follows:—

1. Ten grams of the air-dry earth, which has passed a 3-mm. sieve, are weighed out into a porcelain basin and worked up with 100 c.c. of N/5 hydrochloric acid, the acid being renewed if much calcium carbonate is present. After standing in contact with the acid for one hour, the whole is thrown upon a dried, tared filter and washed until free of acid. The filter and its contents are dried and weighed. The loss represents hygroscopic moisture and material dissolved by the acid.

2. The soil is now washed off the filter with dilute ammoniacal water on to a small sieve of 100 meshes to the linear inch, the portion passing through being collected in a beaker marked at 10, 8·5, and 7·5 cm. respectively from the bottom. The portion which remains upon the sieve is dried and weighed. It is then divided into "fine gravel" and "coarse sand" by means of a sieve with round holes of 1 mm. diameter. The portion which does not pass this sieve is the "fine gravel". This should be dried and weighed. The difference gives the "coarse sand". If required, both these fractions can also be weighed after ignition.

3. The portion which passed the sieve of 100 meshes per linear inch is well worked up with a rubber pestle (made by inserting a glass rod as handle into an inverted rubber stopper), and the beaker filled up to the 8·5 cm. mark and allowed to stand twenty-four hours. The ammoniacal liquid which contains the "clay" is then decanted off into a Winchester quart. This operation is repeated as long as any matter remains in suspension for twenty-four hours. The liquid containing the "clay" is either evaporated in bulk or measured, and, after being well shaken, an aliquot portion taken and evaporated. In either case the dried residue consists of "clay" and "soluble humus". After ignition the residue gives the "clay," and the loss on ignition the "soluble humus". Here minimum value of $v = \frac{1}{10,000}$ cm. per sec., and the minimum diameter of the particles works out to ·0013 mm.

4. The sediment from which the "clay" has been removed is worked up as before in the beaker, which is filled to the 10 cm. mark and allowed to stand for 100 seconds. The operation is repeated till the "fine sand" settled in 100 seconds is clean, when it is collected, dried and weighed.

Here minimum value of $v = \frac{1}{10}$ per second; the calculated minimum diameter = ·037 mm.

5. The turbid liquid poured off from the "fine sand" is collectedin a Winchester quart, or other suitable vessel, allowed to settle, and the clear liquid syphoned or decanted off. The sediment is then washed into the marked beaker and made up to the 7·5 cm. mark. After stirring, it is allowed to settle for twelve and a half minutes, and the liquid decanted off. The operation is then repeated as before till all the sediment sinks in twelve and a half minutes leaving the liquid quite clear. The sediment obtained is the "silt," which is dried and weighed as usual. The liquid contains the "fine silt," which, when it has settled down, can be separated by decanting off the clear liquid, and dried and weighed.

For silt minimum value of $v = \frac{1}{100}$ cm. per second, minimum diameter of particles = ·012 mm. For fine silt the diameter obviously lies between this value, and the one found for clay.

6. Determinations are made of the "moisture" and "loss on ignition" of another 10 grams of the air-dry earth. The sum of the weights of the fractions after ignition + loss on ignition + moisture + material dissolved in weak acid should approximate to 10 grams.

7. It is advisable to make a control determination of the "fine gravel" in a portion of 50 grams of the air-dry earth. The soil should be treated with acid, as in 1, and after that is removed by decantation may be at once treated with dilute ammonia and washed on the sieve with 1 mm. round holes. The "fine gravel" left on the sieve is then dried and weighed.

The American method is somewhat different. The breaking down of the aggregates is brought about by physical means—*e.g.* violent shaking—and sedimentation is sometimes hastened by a centrifugal apparatus. Hilgard does not adopt a sedimentation method but proceeds in the converse manner; he collects and weighs the particles carried off by successive streams of water of varying velocity. Full details are given in *Bull.* 24, *Bureau of Soils*, 1904, and in Wiley's *Agricultural Analysis*, vol. i., where the continental methods are also described.

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